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EVALUATION OF PERFORMANCE AND COSTS ASSOCIATED WITH ANAEROBIC DECHLORINATION TECHNIQUES

Revision 02

PHASE I SITE SURVEY

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ACRONYMS AND ABBREVIATIONS

μg/L	micrograms per liter
AEC	Army Environmental Center
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AFRL	Air Force Research Laboratory
atm	atmospheres
bgs	below ground surface
CAHs	chlorinated aliphatic hydrocarbons
CCAS	Cape Canaveral Air Station
cis-1,2-DCE	*cis*-1,2-dichloroethene
CH_4	methane
CMS	Corrective Measures Study
CO_2	carbon dioxide
CT	carbon tetrachloride
DCE	dichloroethene
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoE	Department of Energy
DoD	Department of Defense
DPT	direct-push technology
ESTCP	Environmental Security Technology Certification Program
gpm	gallons per minute
H_2	hydrogen
HCl	hydrochloric acid
HRC®	Hydrogen Release Compound
ITRC	Interstate Technology and Regulatory Council
K_{oc}	partitioning coefficient between organic carbon and water
$K_s(H_2)$	Monod half-saturation constant
mg/L	milligrams per liter
NAS	Naval Air Station
NFESC	Naval Facilities Engineering Service Center
nM	nanomoles
NSA	Naval Support Activity
ORP	oxidation-reduction potential
Parsons	Parsons Engineering Science, Inc.
PCE	tetrachloroethene
ppm	parts per million
psi	pounds per square inch
RABITT	Reductive Anaerobic Biological In-Situ Treatment Technology
redox	reduction-oxidation
Regenesis	Regenesis Bioremediation Products

RPMs	Restoration Program Managers
TCA	trichloroethane
TCE	trichloroethene
US	United States
USEPA	United States Environmental Protection Agency
VC	vinyl chloride
VFAs	volatile fatty acids

SECTION 1

INTRODUCTION

1.1 PROBLEM STATEMENT

The DoD has identified hundreds of sites with groundwater contaminated with chlorinated aliphatic hydrocarbons (CAHs, which are commonly referred to as chlorinated solvents), and these represent one of the DoDs largest remediation liabilities. At present, the number of commercially-available proven technologies for effective treatment of these sites is limited. One very promising technology is anaerobic dechlorination, which may be an effective method of degrading various forms of chloroethenes, chloroethanes, and chloromethanes dissolved in groundwater. The objective of this report is to summarize relevant performance and cost data on various engineered approaches to stimulate *in situ* anaerobic dechlorination of CAHs.

The most common CAHs targeted for remediation are tetrachloroethene (PCE), trichloroethene (TCE), trichloroethane (TCA), carbon tetrachloride (CT), and their daughter products. A number of different approaches have been or currently are being demonstrated. Numerous universities, government entities, and private industries have applied a wide variety of substrates to promote anaerobic reductive dechlorination. However, the *in situ* enhanced bioremediation approach is not widely used, nor has it gained widespread regulatory acceptance. A comprehensive program to evaluate and compare alternative approaches is needed to assist DoD managers in assessing the application of the technology for their sites and in identifying the optimum approach.

Anaerobic dechlorination can be defined as the biologically-driven reductive degradation of chlorinated compounds. During these reactions, the chlorinated compounds may serve as energetic electron acceptors in catabolic processes, or may be cometabolized, but in either case the compounds are reduced. The most thoroughly studied anaerobic dechlorination pathway is degradation of PCE to TCE to *cis*-1,2-dichloroethene (*cis*-1,2-DCE) to vinyl chloride (VC), and finally to ethene and ethane. For this process to occur, strongly anaerobic conditions are required. These conditions are created by the anaerobic biodegradation of an electron donor, usually a carbon source. It appears that the carbon substrate or intermediate degradation products are fermented, which produces hydrogen (electron donor); the hydrogen produced is then used to replace a chlorine atom (halorespiration), which results in the reduction of the chlorinated compound (electron acceptor). This process can occur naturally in groundwater, supported by natural organic material, and it also may occur in quasi-natural conditions where non-chlorinated organic contaminants such as jet fuel or landfill leachate are present.

When the process occurs naturally, it is considered a component of natural attenuation. Unfortunately, natural attenuation is not sufficient at many sites contaminated with chlorinated compounds to achieve remedial objectives. The addition of organic carbon or gaseous hydrogen to stimulate or enhance the anaerobic dechlorination process has been explored at many sites. Organic carbon sources that have been added to stimulate dechlorination reactions in the subsurface include: lactate, butyrate, acetate, molasses, refined sugars (fructose), hydrogen release compound (HRC™), edible oils, and plant mulch. A variety of injection/application strategies have been proposed and tested. For example, hydrogen can be injected directly in a biosparging application, it can be dissolved in water that is injected, or it can be introduced passively through implanted membranes. Each of these different delivery approaches have specific potential applications, costs, and effectiveness. The objective of this project is to summarize and evaluate each of these engineered approaches and assemble a comprehensive document for use by DoD managers when considering and comparing the alternative approaches to stimulating anaerobic dechlorination processes in contaminated groundwater.

1.2 PROJECT DESCRIPTION

The project approach is to collect publicly-available information on the state-of-the-art in application of anaerobic dechlorination technologies, conduct a comparative analysis of the results, and produce a report detailing the state-of-the-art and providing lessons learned on how to promote effective applications. The overall project is to be conducted in two phases:

Phase I – Site Survey. This task involves completion of a literature review and site survey that focuses on collecting available information on the state-of-the-art in application of anaerobic dechlorination technologies. This interim report summarizes the information collected during the Phase I Site Survey. An expert working group was assembled to assist in preparing this report, providing an unbiased consensus of the results and conclusions. The objectives and scope of this report are more fully described in Section 2.

Phase II – Detailed Site Surveys and Evaluations. A second phase will review information regarding the electron donor sources and application approaches compiled in this Phase I Site Survey interim report. The Navy, the Air Force Center for Environmental Excellence (AFCEE), and the Army Environmental Center (AEC) are cooperating to develop a guidance document for DoD restoration program managers (RPMs) and their contractors to use when considering enhanced bioremediation as a remedial alternative for chlorinated compounds in groundwater. The Phase II effort will support development of this anaerobic dechlorination guidance document, including a literature review, a section on lessons learned, and cost estimating tools.

1.2.1 Project Team

The project team for the Phase I Site Survey consists of NFESC and Parsons with support from government, industry, and university experts. The principal investigator is Mr. Bryan Harre with NFESC. NFESC provides overall technical direction for the project. The Parsons team consists of the project manager and principal geologist, Mr. Bruce Henry; the technical director and principal engineer, Mr. Doug Downey; and staff engineers, Mr. Karthik Narayanaswamy and Mr. Daniel Griffiths. Dr. Robert Hinchee of Battelle Memorial Institute, Dr. Laurie LaPat-

Polasko of Geomatrix Consultants, Dr. James Mercer of GeoTrans, Inc., and Dr. James Gossett of Cornell University provided technical review and advice.

1.2.2 Report Organization

This report contains six sections, including this introduction, and two appendices. Section 2 more fully describes the objectives and scope of this Phase I Site Survey. Section 3 describes the scientific basis of the anaerobic dechlorination technology and the engineered delivery approaches and substrates used to implement the technology. Section 4 summarizes and provides a discussion of Phase I survey sites relative to substrate used, the selected remedial design, the objectives of the application, and the success to date of the remedial system to achieve those objectives. Section 5 provides conclusions of the Phase I Site Survey and recommendations concerning Phase II work. Section 6 contains references cited in the text of this report, as well as those primary references used to compile the Phase I data tables. Appendix A contains contact information for key project personnel, and Appendix B contains the Phase I project database.

SECTION 2

OBJECTIVES AND SCOPE

The overall objective of this project is to assess the current state-of-the-art for anaerobic dechlorination technologies, and to better understand the site conditions and technology approaches that should lead to successful remediation of dissolved CAH contamination. The project was proposed for two phases, a Phase I Site Survey interim report and a Phase II Technology Status Review. This report presents the results of the Phase I Site Survey interim report.

2.1 PHASE I SITE SURVEY OBJECTIVES

The objectives of the Phase I Site Survey are to identify, collect, and summarize the following information:

- Where enhanced bioremediation using anaerobic dechlorination techniques has been used;
- The scale at which it was deployed;
- The specific substrates used;
- The delivery configuration employed;
- The cost to construct, operate and maintain, and monitor the technology; and
- An evaluation of the adequacy of the data collection to measure success or failure.

2.2 PHASE I SCOPE

The site survey involved contacting technology vendors, government entities, university researchers, and regulators, and reviewing government databases and web sites (e.g., DoD, Department of Energy [DoE], US Environmental Protection Agency [USEPA], Interstate Technology and Regulatory Council [ITRC] Cooperative Working Group) to identify sites where anaerobic dechlorination has been deployed. In most cases, references were reviewed and site project managers were contacted to collect the following information:

- The current status of the project;
- The scale at which anaerobic dechlorination was deployed;
- The substrate and amendments used;
- The chlorinated compounds and media treated;

- The extent of available site data (hydrogeologic characterization, nature and extent of contamination, and geochemistry);
- The delivery system method and configuration;
- Operation and maintenance requirements;
- Performance monitoring strategies;
- Capital construction, substrate, and monitoring costs;
- The responsible parties and regulators involved; and
- Information regarding the success or failure of the project.

Results of the Phase I Site Survey are presented herein, and will be used to select several sites for more detailed profiling in Phase II. Table 2.1 is a summary of the 93 Phase I Survey sites sorted by substrate. The table includes the primary contaminants targeted for remediation, and the number of bench-, pilot-, or full-scale studies conducted (many sites had both pilot- and full-scale applications). Remedial objectives and further discussion of these sites are included in Sections 3.2 and 4.

Additional sites were identified (Table 2.1), but insufficient data were available to warrant incorporation into the site survey tables presented in Section 4. These sites are included in the database in Appendix B for future reference. Regenesis Bioremediation Products (Regenesis) reports up to 410 applications of HRC™ (Koenigsberg, 2002). It is not known how many of these applications are bench-, pilot-, or full-scale applications. ARCADIS Geraghty & Miller (ARCADIS) reports 88 applications of molasses (ARCADIS, 2002), 70 of which target chlorinated organic compounds. Of these 70 applications, approximately are 35 are pilot-scale applications, 29 are full-scale applications, and 6 are at earlier stages (bench-scale or design of a pilot-test). Many of the above reported sites are not documented in the literature; thus, the number of sites in the survey for each substrate are not necessarily proportional to the total number of actual applications.

2.3 FUTURE PHASE II OBJECTIVE AND SCOPE

A second phase will be performed to further evaluate selected Phase I sites in order to determine why selected substrates were used, rationale for design parameters, estimation of costs to apply a particular substrate and configuration, and the reasons differing anaerobic dechlorination applications succeeded or failed.

At the conclusion of the Phase II evaluation, lessons learned on the selection and use of anaerobic dechlorination techniques will be developed. Lessons learned will be the basis for determining which dechlorination technologies have the most promise to support successful and cost-effective remediation of dissolved CAH contamination. This work will be incorporated into a joint Air Force, Navy, and Army bioremediation guidance document.

TABLE 2.1
SUMMARY OF PHASE I SURVEY SITES

Substate Type	Sites Identified[a/]	Sites Included In Survey[b/]	Survey Sites: Primary Contaminants: PCE	TCE	Other	Survey Sites[c/]: Bench-Scale Studies	Pilot-Scale Studies	Full-Scale Applications
DISSOLVED SUBSTRATES								
Lactate	22	14	7	11	8	1	11	3
Butyrate	3	3	1	3	2	3	3	0
Molasses	19	15	7	9	5	0	9	9
Fructose	1	1	0	1	0	0	1	0
Lactose	1	1	1	1	1	0	0	1
Acetate	3	3	1	2	1	0	3	0
Methanol/Acetate	2	2	2	2	2	1	2	0
Sodium Benzoate	1	1	0	0	1	0	1	0
Ethanol	1	1	1	0	0	0	1	0
SEMI- OR SLOWLY-SOLUBLE SUBSTRATES								
HRC™	47	35	17	23	15	0	26	12
Edible Oils	17	10	5	9	7	1	9	3
SOLID SUBSTRATES								
Bark Mulch	3	3	0	2	2	1	2	3
Chitin	1	1	0	1	1	0	1	0
HYDROGEN								
Direct Hydrogen Injection	3	3	1	2	1	1	3	0
TOTALS	124	93	43	66	46	8	72	31

[a/] The number of sites included in this survey is a subset of the total number applications cited by technology vendors. For example, Regenesis Bioremediation Products (Koenigsberg, 2002) cites up to 410 applications of HRC™, and ARCADIS Geraghty & Miller (ARCADIS, 2002) cites 88 applications of molasses.

[b/] Not all sites had sufficent data available to include in the site survey tables presented in Chapter 4. However, those sites identified, but not included in the tables, are listed in the database in Appendix B for future reference.

[c/] Many sites have bench-, pilot-, and/or full-scale applications.

SECTION 3

TECHNOLOGY DESCRIPTION

3.1 ANAEROBIC REDUCTIVE DECHLORINATION

The process of anaerobic reductive dechlorination has been well documented. Recent discussions of the overall process can be found in Alexander, 1999; Wiedemeier *et al*., 1999; USEPA, 2000a; and Suthersan, 2001. Many other research papers on particular aspects of the process are referenced in this text. Because anaerobic reductive dechlorination of chlorinated contaminants is dependent on many environmental factors (e.g., anaerobic conditions, fermentable substrates, hydrogen generation, and appropriate microbial populations), a comprehensive discussion of the topic is beyond the scope of this report. The following sections provide a brief description of the process; the reader is referred to the above references for further details.

Patents have been developed for many of the processes used to implement *in situ* biodegradation of CAHs by anaerobic dechlorination. As with many remediation techniques developed using government funds and contracts, the government is generally granted free license to use the technology as part of the contractual agreement. However, the authors caution the reader to explore the application of existing patents when considering any anaerobic dechlorination technology.

3.1.1 Halorespiration and Fermentation

The most important process for the biodegradation of the more highly chlorinated solvents is halorespiration, commonly referred to as reductive dechlorination. During this process, the chlorinated hydrocarbon is used as an electron acceptor and a chlorine atom is removed and replaced with a hydrogen atom. In general, reductive dechlorination occurs by sequential dechlorination. For example, the chlorinated ethenes are transformed from PCE to TCE to DCE to VC to ethene. Depending upon environmental conditions and presence/absence of suitable microbes, this sequence may be interrupted, with other processes acting upon the degradation products.

Reductive dechlorination of chlorinated solvent compounds is associated with the generation of daughter products and an increase in the concentration of chloride ions. Reductive dechlorination affects each of the chlorinated compounds differently. For example, of the chlorinated ethenes, PCE and TCE are the most susceptible to reductive dechlorination because they are the most oxidized. Conversely, VC is the least susceptible to reductive dechlorination because it is the least oxidized of these compounds. Therefore, the potential exists for VC to accumulate in a

treatment system when the rate at which it is generated is greater than the rate at which it degraded. This is a common concern because VC is considered more toxic than the other chlorinated ethenes.

Reductive dechlorination occurs under sulfate-reducing and methanogenic conditions. Because chlorinated compounds are used as electron acceptors during reductive dechlorination, there must be an appropriate electron donor present. The electron donor used by most reductive dechlorinating microbes is molecular hydrogen, which may be produced via primary or secondary fermentation of a variety of organic substrates. Potential sources of molecular hydrogen include natural organic matter, fuel hydrocarbons, landfill leachate, or the organic substrates that are the focus of this technology review.

Significant progress has been made in recent years in understanding the biochemistry of halorespiration. It is now understood that halorespiration is typically based on the following generalized reduction-oxidation (redox) reaction:

$$H_2 + C\text{-}Cl \Rightarrow C\text{-}H + H^+ + Cl^-$$

where C-Cl represents a carbon-chloride bond in a chlorinated solvent. In this reaction, hydrogen (H_2) is the electron donor, which is oxidized, and the chlorinated solvent is the electron acceptor, which is reduced. Although a few other electron donors besides hydrogen have been identified which can drive halorespiration, these compounds also are fermentation products. Many pure cultures isolated to date which can completely dechlorinate PCE to ethene require hydrogen as the electron donor (Maymo-Gatell *et al.*, 1997; Fennell and Gossett, 1997). Therefore, hydrogen appears to be the most important electron donor for halorespiration.

While chlorinated compounds have been observed to be degraded in a variety of laboratory systems, it is now apparent that these systems likely contained at least two distinct guilds of bacteria. One guild ferments the organic carbon to produce hydrogen, and another guild utilizes the hydrogen as an electron donor for halorespiration. Only recently have researchers begun to fully recognize the role of hydrogen as the electron donor in the reductive dechlorination of PCE and TCE (Holliger *et al.*, 1993; Gossett and Zinder, 1996; Smatlak *et al.*, 1996; Ballapragada *et al.*, 1997).

Under natural conditions, fermentation is the process that generates the hydrogen used in reductive dechlorination. Fermentation is a balanced redox reaction, in which different portions of a single substrate are oxidized and reduced, yielding energy. Fermentation does not require an external electron acceptor, such as oxygen, nitrate, or a chlorinated solvent. Fermentation yields substantially less energy per unit of substrate compared to oxidation reactions, which utilize an external electron acceptor; thus, fermentation generally occurs when these external electron acceptors are not available. Bacterial fermentation can be divided into two categories:

- **Primary fermentation:** The fermentation of primary substrates such as sugars and amino acids yields acetate, formate, carbon dioxide (CO_2) and H_2, but also yields ethanol, lactate, propionate, and butyrate. While primary fermentation often yields H_2, production of H_2 is not required for these reactions to occur.

- **Secondary fermentation:** The fermentation of primary fermentation products such as ethanol, lactate, propionate, and butyrate yielding acetate, formate, H_2, and CO_2. Bacteria, which carry out these reactions, are called *obligate proton reducers* because the reactions must produce hydrogen in order to balance the oxidation of the carbon substrates. These secondary fermentation reactions are energetically favorable only if hydrogen concentrations are very low (10^{-2} to 10^{-4} atmospheres [atm] or 8,000 nanomoles [nM] to 80 nM dissolved hydrogen, depending on the fermentation substrate). Thus, these fermentation reactions occur only when the produced hydrogen is utilized by other bacteria, such as methanogens. The process by which hydrogen is produced by one strain of bacteria and utilized by another is called interspecies hydrogen transfer.

In the absence of external electron acceptors, the hydrogen produced by fermentation will be utilized by methanogens (methane-producing bacteria). In this case, the ultimate end products of anaerobic metabolism of carbon substrates will be methane (CH_4) (the most reduced form of carbon) and CO_2 (the most oxidized form of carbon). However, in the presence of external electron acceptors (halogenated organics, nitrate, sulfate, etc.), other products will be formed.

There are many carbon substrates which are naturally fermented at chlorinated sites and that result in the generation of hydrogen. Examples of easily fermentable organics include acetone, sugars, and fatty acids. In addition, some groundwater naturally contains high concentrations of organic compounds. The purpose of adding an organic substrate to the subsurface is to provide additional organic carbon that can be fermented to produce hydrogen.

In summary, hydrogen is generated by fermentation of non-chlorinated organic substrates including fuels, naturally-occurring organic carbon, and a variety of other compounds, including carbohydrates, sugars, alcohols, volatile fatty acids (VFAs), and vegetable oils. Methanogens require fermentation products as substrates; therefore, methane production is clear evidence of *in situ* fermentation. Fermentation produces hydrogen that is the primary electron donor utilized for reductive dechlorination of chlorinated solvents.

3.1.2 Anaerobic Cometabolic Dechlorination

When a chlorinated compound is biodegraded via cometabolism, the degradation is catalyzed by an enzyme or cofactor that is fortuitously produced by the organisms for other purposes. The organism receives no known benefit from the degradation of the chlorinated compound. Rather, the cometabolic degradation of the chlorinated compound may in fact be harmful to the microorganism responsible for the production of the enzyme or cofactor (McCarty and Semprini, 1994).

Cometabolism is best documented in aerobic environments, although it also may occur under anaerobic conditions. In general, cometabolic dechlorination has been observed in the presence of acetogenic and methanogenic bacteria (Suthersan, 2001). Complete dechlorination of PCE to ethene by pure microbial cultures has not been observed; rather, complete cometabolic dechlorination is usually observed with mixed anaerobic cultures. However, it is often difficult to distinguish between cometabolic and metabolic dechlorination. Because the organisms that cause anaerobic cometabolic dechlorination are ubiquitous in the subsurface, cometabolic

dechlorination is likely responsible for some degradation of chlorinated compounds (Gossett and Zinder, 1996). However, concerns that the process is slow and incomplete relative to metabolic dechlorination (Gossett and Zinder, 1996) suggests that this strategy may be difficult to implement.

3.1.3 Competing Anaerobic Microbial Processes

As hydrogen is produced by fermentative organisms, it is rapidly consumed by other bacteria. The utilization of hydrogen by non-fermentors is known as interspecies hydrogen transfer and is required for fermentation reactions to proceed (Wiedemeier *et al*., 1999). Although hydrogen is a waste product of fermentation, it is a highly reduced molecule, which makes it an excellent high-energy electron donor. A wide variety of bacteria can utilize hydrogen as an electron donor: denitrifiers, iron reducers, sulfate reducers, methanogens, and halorespirators. Thus, the production of hydrogen through fermentation does not, by itself, guarantee that hydrogen will be available for halorespiration. For dechlorination to occur, halorespirators must successfully compete against the other hydrogen utilizers for the available hydrogen.

Smatlak *et al*., (1996), suggest that the competition for hydrogen is controlled primarily by the Monod half-saturation constant $K_s(H_2)$, the concentration at which a specific strain of bacteria can utilize hydrogen at half the maximum utilization rate. They measured $K_s(H_2)$ values for halorespirators and methanogens of 100 nM and 1,000 nM, respectively. Based on this result, they suggested that halorespirators would successfully compete for hydrogen only at very low hydrogen concentrations. This implies that the selection of an organic substrate whose fermentation results in a slow, steady, and low-level release of hydrogen (electron donor) over time could maximize dechlorination potential while minimizing methanogenic competition for the available hydrogen (Smatlak *et al*., 1996).

Ballapragada *et al*., (1997), point out that competition for hydrogen also depends on additional factors including the bacterial growth rate (relative cell yields) and maximum hydrogen utilization rate. While they concluded that dechlorinating bacteria may out-compete methanogens for hydrogen utilization at low hydrogen concentrations, they also concluded that dechlorinators can compete successfully with methanogens up to a hydrogen partial pressure of 100 parts per million (ppm). Because hydrogen seldom exceeds 100 ppm in methanogenic environments, dechlorinators should normally have an advantage.

In summary, site-specific geochemical characteristics and microbial populations have a significant impact on the rate and relative utilization of electron donor (i.e., hydrogen). Dechlorinators will likely have a competitive advantage over methanogens at lower hydrogen partial pressures. Biodegradation at higher hydrogen partial pressures would require more electron donor as a larger portion of available hydrogen would be utilized by methanogenic bacteria. Often this is compensated for by increasing the amount of organic substrate added to the system.

3.2 REMEDIAL APPROACHES AND *IN SITU* DELIVERY TECHNIQUES

Remediation of chlorinated compounds that are dense non-aqueous phase liquids (DNAPLs), sorbed to the aquifer matrix, and/or dissolved in groundwater has been problematic for the DoD.

Two general approaches to remediating chlorinated solvent sites have emerged: source reduction and plume restoration. The following subsections discuss these remedial approaches and the delivery techniques and configurations commonly used.

3.2.1 Source Reduction

Many of the sites in the Phase I Site Survey were configured for source reduction, although other remedial objectives often were established. Difficulties associated with delineation and characterization of DNAPL or sorbed CAH sources often complicates source removal efforts. In many cases, an apparent plume "hotspot" is the basis for delineating a source area. Thus, addition of organic substrates is typically applied across a broad area of the plume source or "hotspot" area to compensate for the difficulty in DNAPL source characterization. Under these circumstances, substrates are usually delivered into the source area via recirculation wells or well fields, or by direct injection of the substrate into an injection grid.

Biodegradation of CAH mass does not directly apply to DNAPL; rather, degradation of CAHs occurs primarily in the dissolved (aqueous) phase. Therefore, remediation of source zones may be limited by dissolution and diffusion processes controlling the rate of mass transfer from DNAPL to the dissolved phase. However, enhanced anaerobic dechlorination will be more effective than conventional pump and treat for source remediation because degradation of contaminant mass and lowering of concentrations in the dissolved phase causes a greater concentration gradient between groundwater and the DNAPL. Experimental studies (Carr *et al*., 2000; Cope and Hughes, 2001) have demonstrated that dechlorinating bacteria can substantially reduce the time required to deplete the PCE fraction of a simulated NAPL source zone. This occurs primarily by depleting aqueous-phase PCE in the direct vicinity of the NAPL, thereby increasing the overall mass-transfer (dissolution) of PCE from the NAPL into solution. Furthermore, these studies point out that depletion of total chlorinated ethenes from a NAPL is dependent not only on the rate of dechlorination, but also upon the extent of dechlorination. Sequential dechlorination of PCE results in the formation of TCE, DCE, and VC. These daughter products will partition into existing NAPL and cause temporal changes in NAPL composition. But because the partition coefficients decrease as the chlorinated ethenes become more reduced (i.e., aqueous solubility increases), the daughter products will partition more strongly into the aqueous phase and an increase in the total chlorinated ethene removal rate from the NAPL is possible (Carr *et al*., 2000 and Payne *et al*., 2001).

The ability of some substrates to act as surfactants and mobilize DNAPL or sorbed CAH mass into the dissolved phase where it is available for biodegradation is being studied, and may further promote the effectiveness of anaerobic dechlorination applications to remediate DNAPL and sorbed sources. Byproducts of microbial degradation also may include "biosurfactants" that increase the amount of DNAPL mass that is available (e.g., desorbed) for reductive dechlorination. Therefore, anaerobic dechlorination techniques have the potential to accelerate remediation of DNAPL sites.

Recirculation strategies may involve one or more circulation wells where vertical circulation is obtained by simultaneously extracting and reinjecting groundwater within a single well bore with upper and lower screened intervals. Circulation well fields also are deployed where horizontal flow and circulation are achieved by extraction at a downgradient location and injection at an

upgradient location. In either scenario, dissolved substrates (e.g., lactate or molasses) are added to the circulation treatment stream and delivered to the aquifer via the induced groundwater flow field. Recirculation well fields are also applied to broader plume restoration.

Direct injection into a source area may be accomplished by injection into temporary or permanent injection wells, or through a direct-push rod. Both scenarios have been applied. Both dissolved substrates and semi- or slowly-soluble substrates (e.g., HRC™ or edible oils) may be injected in this manner. As with recirculation techniques, uniform distribution of the substrate may be problematic due to aquifer heterogeneity. Dispersion and/or advective groundwater flow following direct injection is desirable to further distribute dissolved substrate and create a larger passive reaction zone (relative to recirculation techniques).

3.2.2 Plume Restoration and Containment

In many cases, remedial systems were configured to treat and/or contain dissolved chlorinated solvent plumes. Often, the approach has been to intercept the contaminant plume and use treatment as a restoration or containment measure. Mass destruction is achieved by stimulating reductive dechlorination of dissolved contaminants. Containment may be achieved via hydraulic control through recirculation or by configuring the application as a permeable reactive barrier. Recirculation well fields typically employ injection wells in a plume while extraction is employed at a downgradient point of containment. Where source areas are poorly defined, widely distributed, or inaccessible, a permeable reactive barrier may be employed to intercept and treat a contaminant plume at a property boundary or point of compliance, in order to prevent migration to potential receptors.

3.3 ORGANIC SUBSTRATE ALTERNATIVES

As described above, fermentation and hydrogen generation generally drive reductive dechlorination. Direct addition of molecular hydrogen (gas) is the most direct approach to stimulate the process. Alternately, a number of primary fermentable substrates have been utilized for this purpose. One advantage of using a carbon-based organic substrate instead of direct hydrogen injection is that a carbon-based substrate provides carbon required for microbial growth, while hydrogen alone does not. Therefore, groundwater systems lacking in natural organic carbon may benefit from use of a carbon-based substrate to stimulate growth of a microbial population capable of degrading chlorinated compounds. In addition, complex microbial ecosystems resulting from injection of complex substrates (versus hydrogen alone) may be beneficial in interspecies transfer of various micronutrients (vitamins, growth-factors) to the dechlorinators. *Dehalococcoides Ethenogenes,* for example, cannot subsist on molecular hydrogen and acetate alone, but has requirements for unidentified vitamins and growth factors it gets from other members of the ecosystem (Gossett, 2002).

Substrates for which case studies have been surveyed for this study include (Table 2.1): lactate or lactic acid (14 sites), butyrate or butyric acid (3 sites), acetate (3 sites), molasses (15 sites), fructose (1 site), lactose (1 site), methanol/acetate (2 sites), ethanol (1 site), sodium benzoate (1 site), HRC™ (35 sites), edible oils (10 sites), mulch (3 sites), chitin (1 site), and gaseous hydrogen (3 sites). Discussion of these substrates follows. Other potential substrates that have been identified, but for which case studies are not yet available include gaseous methane, milk,

cheese whey, flour, cellulose, tetrabutyl orthosilicate, and oleate (Suthersan, 2001; Yang and McCarty, 2000). Biomass produced by microbial growth also has been shown in the laboratory to be a suitable secondary substrate for anaerobic dechlorination (Yang and McCarty, 2000; Sin Chit To, 2001).

3.3.1 Dissolved Phase Substrates

Substrates applied as a dissolved phase offer the greatest potential for uniform distribution throughout the aquifer matrix relative to substrates applied as a viscous, semi-solid, or solid phase. Lactate and molasses are the most common substrates applied as a dissolved phase. Because dissolved substrates will travel with advective groundwater flow, they typically are applied in a continuous or periodic (pulsed) mode to maintain a specified treatment zone.

Lactate is generally applied in the form of sodium lactate at a ratio of 3 percent to 60 percent by weight. Because solutions of sodium lactate are more dense than water, there are potential density effects during substrate migration. While fermentation of lactate to acetate may produce free hydrogen, lactate also may be fermented to a secondary fermentation product, propionate, which in turn can be fermented to hydrogen and acetate. Thus, lactate may become a propionate source *in situ*.

Molasses is a syrup produced during the refining of raw sugar. While molasses is comprised primarily of sugars, it also may contain other constituents such as sulfur, sulfate, and metals that may be of potential concern. Therefore, additional processing of the molasses may be required to remove undesirable impurities, or a higher grade molasses may be necessary. Molasses is comprised mostly of sucrose, and is typically dissolved in water at concentrations of 10 to 40 percent by volume for injection. Sugars generally degrade to fermentation products such as metabolic acids and alcohols; thus, hydrogen generation is primarily achieved as a result of secondary fermentation.

Other dissolved substrates that were used at surveyed sites include butyrate, propionate, yeast extract, and a lactate/benzoate mixture. These sites were part of the Reductive Anaerobic Biological *In Situ* Treatment Technology (RABITT) protocol study funded by ESTCP (1998). The RABITT protocol promotes the use of VFAs and alcohols to stimulate reductive dechlorination.

3.3.2 Slowly-Soluble Substrates

Slowly-soluble substrates include HRC™ and edible (vegetable) oils. These substrates are intended as slow-release substrates where a single or limited number of injections are sufficient to remediate a site. These substrates rely more on dissolution and diffusion for delivery throughout the aquifer matrix relative to dissolved substrates.

HRC™ (a trade mark of Regenesis Bioremediation Products) is a proprietary polylactate ester designed as a slow-release electron donor. Lactic acid is released in the subsurface environment upon hydration. Groundwater hydrolyzes the ester linkage and separates the polylactic acid complex from a glycerol backbone. The polylactic acid complex comprises approximately 50 percent of the HRC™ product, while the glycerol backbone comprises the rest of the material.

The polylactic acid complex further breaks down into lactic acid molecules, which can be fermented (directly or indirectly) to produce hydrogen. The time-release characteristics of HRC™ differentiate it from direct application of lactate, and allows for fewer applications (often only one) of the substrate.

The vegetable oil used at the survey sites was primarily refined soybean oil, commonly referred to as salad oil. More recently, the vegetable oil has been injected as an oil-in-water emulsion ranging from 5 to 35 percent oil. The primary purpose of the emulsion is to enhance distribution of the oil in the subsurface. Common vegetable oils are less dense than water, and the injection of oil at greater than residual phase saturations (greater than approximately 25 to 35 percent) may result in vertical upward migration of the vegetable oil in relatively homogeneous aquifers. Preparing an oil-in-water emulsion with small oil droplet size relative to the formation pore-throat size allows the emulsion to travel more freely into the injection treatment zone. Lecithin (a natural component of unrefined vegetable oil), Polysorbate 80, and/or glycerol mono-oleate may be used as emulsifiers to create more stable emulsions. Vegetable oil primarily degrades to VFAs such as propionate, butyrate, and acetate, which are subsequently fermented to produce hydrogen for reductive dechlorination.

3.3.3 Solid Phase Substrates

Solid phase substrates include mulch and chitin. Mulch is generally obtained from shredding and chipping of tree and shrub trimmings, and is actively composted prior to emplacement to provide active microbial populations for further degradation of the substrate in the subsurface. Mulch is primarily composed of cellulose, but "green" plant material is typically incorporated to provide a source of nitrogen for microbial growth. Degradation of the substrate by microbial processes in the subsurface provides a number of breakdown products, including metabolic acids. While the nature of the breakdown products and metabolic acids produced by degradation of mulch are not well known, they likely provide secondary electron donors or fermentable substrates for hydrogen generation.

Chitin is best known as the structural component of the shells of crustaceans, but also is present in many other living organisms. Chitin is the most plentiful natural polymer next to cellulose (Sorenson *et al*., 2002). Once chitin is emplaced in the subsurface, it is slowly degraded, producing a slow-release source of electron donor and nitrogen. Chitin is primarily degraded to VFAs such as propionate and isovalerate (Sorenson *et al*., 2002), which provide secondary electron donors or fermentable substrates for hydrogen generation.

Solid-phase substrates generally cannot be emplaced by injection and subsequent flow through the aquifer matrix. Typically, these substrates are emplaced in a trench or excavation, and therefore are deployed in a permeable reactive barrier configuration, versus a source reduction measure. The chitin application described in Section 4.3.2 is an exception, because the chitin was injected in a slurry form by hydraulic fracturing of the formation. This technique can be used to promote either source reduction or downgradient plume treatment.

3.3.4 Gaseous Hydrogen

The role of H_2 as an electron donor is widely recognized in controlling the anaerobic dechlorination of CAHs. Direct injection of gaseous hydrogen (e.g., biosparging) has been shown to stimulate anaerobic dechlorination, and is potentially a simple and low-cost treatment approach (Newell *et al*., 2000 and 2001). Direct hydrogen addition may promote rapid dechlorination. However, unlike other substrates, hydrogen itself does not provide a source of carbon for microbial growth. Therefore, gaseous hydrogen may best be applied in areas where natural organic carbon levels are sufficient to develop the redox conditions necessary for anaerobic dechlorination and to support microbial growth of halorespirating organisms. As noted earlier, complex ecosystems arising from injection of complex substrates (versus hydrogen alone) may be beneficial in interspecies transfer of various micronutrients (vitamins, growth-factors) to the halorespirators.

Hydrogen also may be delivered to the aquifer by dissolving it into groundwater prior to injection, through controlled release reactions (i.e., oxidation of metals or cations), or by permeable membranes.

3.3.5 Nutrient Amendments

Substrate amendments often are utilized to provide sufficient nutrients for microbial growth. Under natural conditions, the aquifer may contain suitable amounts of trace nutrients for microbial growth. However, the nutritional demand imposed by rapid microbial growth in response to addition of a carbon substrate may exceed the capacity of the aquifer system. Substrate nutritional amendments generally include nitrogen and phosphorous, yeast extracts, and vitamin B_{12}. Common forms of nitrogen and phosphorous include ammonia and commercial fertilizers. Yeast extracts also are used to provide nutritional needs for rapid microbial growth.

In addition, fermentation of complex substrates to metabolic acids and hydrochloric acid (HCl) during dechlorination may decrease the pH significantly in low-alkalinity systems. Lowering of pH to below 5 or 4 standard units may inhibit growth of dechlorinating microbes. Therefore, pH buffer amendments may be required in groundwater systems with insufficient natural buffering capability

3.3.6 Bioaugmentation

Bioaugmentation may be utilized at a site when the presence of an appropriate population of microbial halorespirators is not present, or when dechlorination does not proceed to completion. Bioaugmentation involves the injection of a microbial amendment comprised of non-native organisms known to carry dechlorination of the targeted chlorinated compounds to completion. The presence of *Dehalococcoides Ethenogenes* or related *Dehalococcoides* microorganisms has been linked to complete dechlorination of PCE to ethene in the field (Majors *et al*., 2001; Hendrickson *et al*., 2002). *Dehalococcoides* microorganisms were found to be present at 21 of 24 sites where dechlorination was occurring in a study by Hendrickson *et al*. (2002). While the presence of these organisms may be nearly ubiquitous in the environment, they may not necessarily be present or able to proliferate under all subsurface conditions.

Two bioaugmentation approaches are generally employed (Suthersan, 2001). In the first approach, dechlorinating organisms and amendments are added to complement or replace the native microbial population. The intent of this approach is for the introduced microbial population to survive and multiply, or to occupy a specific niche in the environment for long-term degradation of the targeted compounds. In the second approach, a large quantity of dechlorinating organisms are added to the treatment zone to degrade a significant amount of the contaminant before these organisms expire or become inactive. Additional amendments may be made, but the long-term survival of the microbial population is not a primary goal.

While bioaugmentation appears to be a promising technology to enhance anaerobic dechlorination, the record of successful applications is currently limited. Degradation results in laboratory or bench-scale tests may differ substantially from full-scale applications. The difficulty of applying bioaugmentation may be attributed to biotic and abiotic stresses including limitations of nutrients and growth factors in an uncontrolled environment, suppression by competing native microbial populations, metabolism of other non-targeted compounds, inability to distribute the bioaugment uniformly throughout the treatment zone, and inhibitory geochemical conditions such as pH, redox, temperature, and salinity (Suthersan, 2001). Nonetheless, bioaugmentation has been used with success (Henssen *et al*., 2001 and Majors *et al*., 2001). The process is being extensively studied and is being marketed commercially. Therefore, bioaugmentation could be classified as emerging technology for enhanced bioremediation by anaerobic dechlorination.

3.4 ADVANTAGES

Remediation of CAHs in the subsurface, particularly in DNAPL form, is difficult to sometimes technically infeasible due to the density and hydrophobic nature of solvent DNAPLs and aquifer heterogeneity. Highly engineered remedial techniques such as pump-and-treat are costly due to capital expenditures, treatment of secondary waste streams, energy consumption, and long-term operation and maintenance requirements. Conversely, enhanced *in situ* bioremediation via anaerobic dechlorination offers the distinct advantages of:

- **Lower Capital and Maintenance Costs.** Lower capital costs often are realized because substrate addition can be easily accomplished using conventional well installations or by use of direct-push technology (DPT). Systems used to mix substrate and amendments, and for continuous or pulsed injection, are generally widely available, simple to install, and easy to operate. Once a substrate system has been constructed, maintenance is generally routine and inexpensive.
- **Destruction of Contaminants *In Situ*.** Destruction of contaminants *in situ* is highly beneficial because contaminant mass is not transferred to another phase, there is no secondary waste stream to treat, and potential risks related to exposure during remediation are limited.
- **Minimal Disturbance of Infrastructure.** Because substrates are added directly to the subsurface and remediation occurs *in situ*, there is generally little disruption to site activities and infrastructure.
- **Higher Efficiency of Mass Removal.** Some enhanced *in situ* bioremediation techniques have the capability to remediate contaminants sorbed or trapped in the

aquifer matrix in addition to contaminants dissolved in groundwater. Therefore, the time required for subsurface remediation may be less than other approaches (e.g., pump-and-treat).

- **Interphase Mass Transfer.** Initially, mobilization of DNAPL by substrate addition caused concern over mass transfer to the dissolved phase and expansion of groundwater contaminant plumes. More recently however, the ability of many substrates to act as surfactants and to mobilize residual DNAPL or sorbed contaminants to the dissolved phase where they are readily degraded by anaerobic dechlorination has sparked interest in enhanced bioremediation as a more efficient and expeditious method for remediating DNAPL sources where remediation has been dissolution-limited (Carr *et al*., 2000; Cope and Hughes, 2001; and Payne *et al*., 2001). Degradation of organic substrates may yield biosurfactants (e.g., low molecular weight fatty acids) that may increase the mass transfer of DNAPL compounds to the aqueous phase. Degradation of dissolved contaminant mass may increase concentration gradients and dissolution between DNAPL and the dissolved phase. Finally, reduction of chlorinated ethenes may yield intermediate compounds with lower partitioning coefficients between organic carbon and water (K_{oc}) that will partition more strongly into groundwater. All these processes act to promote depletion of DNAPL and sorbed contaminant mass.

In general, enhanced bioremediation via anaerobic dechlorination is both less costly than many other engineered remedial options, and can be combined with other treatment options such as soil vapor extraction.

3.5 CONCERNS

In effectively transitioning anaerobic dechlorination research to a commercially viable technology, several issues must be addressed. These issues include, but are not limited to:

- **Type of Substrate.** The variety and quality of organic substrates (electron donors) that are known to stimulate anaerobic dechlorination are subject to debate. In many cases, selection of one substrate over another is promoted based on contractor or vendor experience or by commercial interests.
- **Delivery Efficiency.** The ability to deliver the substrate uniformly into an aquifer matrix is complicated by aquifer heterogeneity and the physical properties of the substrate. Substrate addition may be difficult to implement in low permeability aquifers, or dechlorination may be limited to more permeable zones or preferential flow paths. These problems also affect other remedial techniques such as pump and treat or *in situ* chemical oxidation, and are not necessarily unique to the technology.
- **Design Methodology.** An established methodology for the design of anaerobic dechlorination applications is not apparent. In many cases, design elements such as substrate concentration, injection rates, and injection location and configuration, appear to be selected intuitively without a defensible basis.
- **Regulatory Permits.** Injection, re-injection, or infiltration galleries often require injection or special regulatory permits. In many cases, the state regulatory agency that

approves such injection permits may not be familiar with enhanced bioremediation technologies.

- **Native Microbial Species and Incomplete Degradation Pathways.** Microbial populations (halorespirators) capable of dechlorination of the chlorinated compounds are thought to be nearly ubiquitous in the subsurface environment (Hendrickson *et al*., 2002; Suthersan, 2001). However, the ability of these halorespirators to compete with other native microbial populations, or to complete the degradation of daughter products to final innocuous end products has been an issue at many sites.
- **Enhanced Plume Migration.** Injection of a carbon source may cause significant displacement of groundwater with the resulting potential for plume spreading. The design of the remedial system should account for any undesirable impacts of injecting or recirculating large volumes of substrate or amended groundwater.
- **Site-Specific Limitations.** Individual sites may have natural hydrogeologic, geochemical, or microbial conditions that limit the effectiveness of enhanced bioremediation. Such limitations may include low permeability and an inability to effectively distribute the substrate; high levels or flux of competing electron acceptors (e.g., dissolved oxygen or sulfate); inhibitory conditions (e.g., salinity); or lack of appropriate microbial species and communities. Therefore, adequate site characterization and development of a comprehensive conceptual site model should be part of the site selection process.
- **Secondary Degradation of Water Quality.** While anaerobic dechlorination may be effective in degrading chlorinated solvents, secondary degradation of groundwater quality may occur. Incomplete dechlorination may lead to accumulation of more toxic daughter products (e.g., VC). Changes in groundwater redox conditions may lead to solubilization of metals (e.g., iron, manganese, arsenic) and methane generation.
- **Generation of Noxious Gases.** Stimulating biodegradation also may enhance generation of gaseous byproducts that may degrade groundwater quality (dissolved phase) or accumulate in the vadose zone. These gases include methane and hydrogen sulfide. In particular, caution must be exercised when operating near structures where these gases could accumulate, and monitoring of volatile organic compounds in the vadose zone also may be warranted.
- **Bioclogging.** Injection wells or infiltration galleries may become plugged by microbial growth or mineral precipitation. This effect also may be observed in the aquifer matrix, leading to reduction in hydraulic conductivity.
- **Remediation of DNAPL Sources.** While anaerobic dechlorination has been shown to be a viable remedial approach for dissolved contaminant mass, it is not yet a proven technology for significant DNAPL sources. Therefore, remediation of sites with substantial DNAPL could still be on the order of decades.
- **Time Frame for Remediation.** Enhanced bioremediation via anaerobic dechlorination is not an instantaneous process such as chemical oxidation. The time required to develop the appropriate environmental conditions and to grow a microbial population capable of complete degradation may be on the order of months to years at most sites. Therefore, the technology may require continuous performance monitoring

and system maintenance at a significant cost. While this issue is often a result of inefficient substrate delivery or microbial deficiencies, exposure pathways analysis and remediation endpoints must be carefully considered before applying this approach.

Due to the number of enhanced bioremediation projects that have been initiated, many of these concerns are being resolved by trial and error, or lessons learned. It is the intent of this study to develop a comprehensive database to support a "lessons learned" approach to resolving these issues.

3.6 SUBSTRATE COSTS

Table 3.1 lists the common substrates used for enhanced bioremediation and their cost per unit weight. The cost per pound of the common substrates varies from as little as the handling cost of mulch, up to $6.00 per pound for HRC™. In some cases, special preparation of the substrate increases cost. For example, chitin is a plentiful and inexpensive substrate, but for the application included in the survey it had to be processed to less than a 20-40 mesh sieve size. The addition of nutrient amendments, emulsification (for vegetable oils), or removal of undesirable constituents (e.g., sulfur from molasses) will increase the relative cost of the substrate.

When comparing cost, it is important to note that complex substrates rely on degradation of organic compounds to short-chain VFAs, which can be fermented to produce hydrogen for reductive dechlorination. Even the degradation pathways for lactate can provide differing reductive dechlorination equivalents. Thus, the cost effectiveness of these substrates is also a function of the type and efficiency of the degradation pathways that produce hydrogen, and the degree to which hydrogen is utilized for reductive dechlorination. In many cases, the approach is to provide more substrate mass than is required for stoichiometric conversion of the contaminant mass, particularly because of the need to compensate for competing electron acceptors.

The cost effectiveness of substrate addition also is a function of the cost of the technology required for emplacement and the cost required for multiple or continuous injections. For example, slowly-soluble substrates often are chosen for a single injection application, whereas soluble substrates are often injected continuously or periodically. The necessity for multiple injections will increase the operating cost of the remedial system and the amount of substrate required. In many cases this cost may be warranted, because it is possible to modify the repeated dosage of substrate to create subsurface environmental conditions that favor anaerobic dechlorination.

Cost effectiveness also is a function of the efficiency and rate at which the substrate or system configuration can stimulate anaerobic dechlorination. For example, the capital and operating cost for a recirculation well field may be substantially higher than for a single injection process. However, the short-term capital and operating costs associated with the recirculation system may offset the long-term cost of process monitoring and land-use restrictions that may be required for the single injection system, if the recirculation system is substantially more efficient and timely in achieving remedial objectives and goals.

TABLE 3.1
RELATIVE COSTS, ADVANTAGES, AND DISADVANTAGES OF ORGANIC SUBSTRATES USED FOR ANAEROBIC DECHLORINATION

Substrate	Bulk Price per Pound (dollars)	Advantages	Disadvantages
Sodium Lactate	1.00 to 2.20	• Controlled Rate of Substrate Addition • Potential for More Uniform Distribution	• Requires Continuous or Periodic Injection
Propionate, Butyrate	NA	• Controlled Rate of Substrate Addition • Potential for More Uniform Distribution	• Requires Continuous or Periodic Injection
Methanol	0.05	• Low Cost • Controlled Rate of Substrate Addition • Potential for More Uniform Distribution	• Requires Continuous or Periodic Injection • Questionable Substrate Quality
Ethanol	0.20 to 0.25	• Low Cost • Controlled Rate of Substrate Addition • Potential DNAPL Surfactant	• Requires Continuous or Periodic Injection
Hydrogen Release Compound (HRC™)	6.00	• Slow Release Substrate • Regulatory Acceptance • Widely Used Technology with Regulatory Site Closures	• Higher Cost Relative to Other Substrates
Molasses	0.25 to 0.35	• Controlled Rate of Substrate Addition • Potential for More Uniform Distribution • Widely Used Technology with Regulatory Site Closures • Low Cost	• Requires Continuous or Periodic Injection • Potential Impurities

(Continued)

TABLE 3.1 (Continued)
RELATIVE COSTS, ADVANTAGES, AND DISADVANTAGES OF ORGANIC SUBSTRATES USED FOR ANAEROBIC DECHLORINATION

Substrate	Bulk Price per Pound (dollars)	Advantages	Disadvantages
Sugar (Corn Syrup)	0.25 to 0.30	• Low Cost	• Requires Continuous or Periodic Injection
Vegetable Oil (Food-Grade Soybean Oil)	0.20 to 0.35	• Long-Lasting Substrate Source • Low Cost	• May Require Emulsification
Mulch and Compost	0.00 to 0.25[a/]	• Long-Lasting Substrate Source • Low Cost	• Limited to Shallow Depths due to Emplacement Technologies
Chitin	3.00 – 4.00	• Long-Lasting Substrate Source	• May Require Special Processing
Whey	0.02 to 0.04	• Long-Lasting Substrate Source • Low Cost	• Lack of Experience and Documentation
Cellulose	0.40 to 0.80	• Long-Lasting Substrate Source • Low Cost	• Lack of Experience and Documentation
Hydrogen Gas	0.05 – 0.11 (scf)	• Direct Electron Donor	• Requires Special Handling • Low Aqueous Solubility

[a/] Mulch is often a free commodity in most communities. However, costs up to 20 dollars per cubic yard may be incurred for processing and handling.

SECTION 4

PHASE I SURVEY RESULTS

Phase I results are discussed in this section according to the phase (dissolved, semi- or slowly-soluble, gaseous, and solid) in which the substrate is typically deployed. Table 4.1 is a summary list of the 93 sites surveyed for this study and includes the substrate type, site name (unless confidential), location, primary contaminants targeted for remediation, responsible party, regulatory jurisdiction, remedial objective, scale of application, date of implementation, project status, and references used to collect the data. Approximately 12 to 15 more sites have been identified, but insufficient data for these sites are available to include them in this survey report.

A total of 93 sites were included in the Phase I Site Survey. As shown in Table 4.1:

- Of the 93 sites, 60 were industrial facilities, 30 were DoD facilities, and 3 were DoE facilities.
- The sites were distributed in 32 states across the continental US, and also in England, Japan, and the Netherlands.
- The most prevalent contaminants targeted for remediation were TCE and PCE. Chlorinated ethenes were the reported target compounds for enhanced anaerobic dechlorination; at one site, perchlorate also was targeted.
- Of the 93 sites, lactate was applied at 14 sites, butyrate at 3 sites, acetate at 3 sites, molasses at 15 sites, fructose at 1 site, lactose at 1 site, methanol/acetate at 2 sites, ethanol at 1 site, sodium benzoate at 1 site, HRC™ at 35 sites, edible oils at 10 sites, mulch at 3 sites, chitin at 1 site, and hydrogen at 3 sites.
- Pilot-scale studies were reported for 59 sites, combination pilot-scale and full-scale studies were reported for 9 sites, and full-scale-only studies were reported for 21 sites. The scale of application at 4 sites is currently unknown.
- The earliest reported pilot studies were initiated in 1995 for the Hanford 200 Area Site (January), the Emeryville Manufacturing Facility (August), and the Avco Lycoming Superfund Site (November). The Emeryville and Avco Lycoming pilot systems were expanded to full-scale in 1997.

TABLE 4.1 SUMMARY LISTING OF PHASE I SURVEY SITES

Site Name (Sorted by Substrate)	Site Location	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Project Status/ Follow-up	References
Lactate									
Bachman Road Residential Well Site	Oscoda, MI	TCE, DCE, VC	Industrial	Michigan DEQ	Groundwater remediation	Pilot	September 2000	Ongoing	Lendvay et al., 2001a Lendvay et al., 2001b Abriola et al., 2001b
Area 6, Dover AFB	Dover AFB, DE	TCE, DCE	Air Force	USEPA, Delaware DNREC	Technology demonstration; groundwater remediation	Pilot	April 1998	Implemented Bioaugmentation, Pilot Test Complete	USEPA, 2000a
Former Drycleaning Facility	WI	PCE	Industrial	NA	Source reduction by 50%	Full	August 1997	NA	Koch and Rice, 2001
Test Area North (TAN), INEEL	ID	TCE	DoE	NA	Groundwater remediation	Full	Pilot - November 1998	Process monitoring is ongoing	Sorenson, 2000; Sorenson, 2002
Ogallala Superfund Site	Ogallala, NE	PCE, TCE	Industrial	Nebraska DEQ, EPA Region VII	Technology assessment	Pilot	April 12, 1999	Process monitoring is ongoing	Nebraska DEQ, 2000, Murt et al., 2000
NAS Fallon	Fallon, NV	PCE, TCE, DCE	Navy	NA	Compare enhanced and intrinsic biodegradation rates	Pilot	1998	NA	Magar et al., 1999
Former PEC Industries Site	Orlando, FL	PCE, TCE, DCE, VC	Industrial	NA	Groundwater remediation	Pilot	2001	NA	Dean et al., 2001
Cape Canaveral Facility 1381	Cape Canaveral, FL	TCE, DCE, VC	Air Force	Florida DEP	Treatability study	Microcosm, Pilot	March 1999	Demonstration completed	AFRL et al, 2001
Watertown Industrial Area	Watertown, MA	TCE, DCE	Industrial	Massachusetts DEP	Feasibility study	Pilot	July, 1997	Feasibility study was ongoing as of March, 2000	Murray et al., 2000; Murray et al., 2001
Aerojet Superfund Site	CA	TCE	Industrial	NA	Technology demonstration	Pilot	September, 2000	NA	Cox et al., 2002
Naval Air Station Point Mugu IRP Site 24	CA	TCE, DCE, VC	Navy	NA	Technology demonstration	Pilot	December, 1998	Pilot test was completed in December 1999.	Leigh et al., 2002
Weyerhauser Sycan Maintenance Shop	Beatty, OR	PCE, TCE	Industrial	NA	Feasibility study	Pilot	NA	NA	Vancheeswaran et al., 2001
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	1,1,2,2-PCA, TCE	DoD	NA	Treatability study	Pilot	NA	NA	Jackson et al., 2001
Southern US Industrial Site	Southern US Industrial Site	PCE	Industrial	NA	Groundwater remediation	Full	March 1998	Ongoing	Fam et al., 2001
Molasses									
Avco Lycoming Superfund Site	Williamsport, PA	TCE	Industrial	USEPA	Groundwater remediation	Pilot, Full	Pilot: November 1995 Full: January 1997	Ongoing	National Priorities List Site Narrative, 1990; Horst et al., 2000; USEPA, 2000
Cedarburgh Drycleaners	Cedarburgh, WI	PCE, TCE, DCE	Industrial	WDNR	Soil and groundwater remediation	Full	NA	NA	State Coalition for Remediation of Drycleaners (Cederburgh, Wisconsin)

TABLE 4.1 SUMMARY LISTING OF PHASE I SURVEY SITES (Continued)

Site Name (Sorted by Substrate)	Site Location	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Project Status/ Follow-up	References
Molasses (Continued)									
Industrial Site	Central Ohio	DCE, VC	Industrial	NA	Contaminant mass reduction in a downgradient groundwater plume	Pilot	Phase I: November 1996 Phase II: September 1998 Phase III: June 1999	NA	Peeples et al., 2000
Washington Square Mall	Germantown, WI	PCE	Industrial	Wisconsin DNR	Source reduction with residual natural attenuation	Full	August 1998 - Pilot March 1999 - Full	Site closed	Maierle and Cota, 2001
Manufacturing Facility	Greenville, SC	CT	Industrial	South Carolina Dept. Health & Environmental Control	Site closure	Pilot, Full	Pilot - March 1998 Full - October 2001	Phase 1 ongoing, to be followed by Phase 2 which will treat leading edge of plume	Shetty and Liles, 1999; Horst et al., 2000 Pahr et al., 2002
Crestwood Site	Glendale, WI	NA	Industrial	WDNR	Mass reduction, natural attenuation for low-level residuals	Full	1998	Ongoing	Horst et al., 2000
Emeryville Manufacturing Facility	Emeryville, CA	TCE, DCE	Industrial	SFRWQCB	Reduce average concentration of total chromium and TCE in groundwater by more than 90%	Pilot, Full	Pilot - August 1995 Full - April 1997	Ongoing	Shetty and Liles, 1999; USEPA, 2000b; Horst et al., 2000; Nyer et al., 2000
Manufacturing Facility	Northeastern USA	PCE	Industrial	NA	NA	Full	Pilot - October 1998 Full - April 2000	NA	Nyer et al., 2000 Payne et al., 2001
Nuclear Fuel Services Site	Erwin, TN	PCE, TCE	DOE	NRC, TDEC-DSWM, EPA Region IV	Reduce VOC concentrations, contain plume migration	Pilot	August 2000	Full scale implementation is scheduled for 2nd quarter, 2002	Arcadis, 2002 Morie et al., 2002
TRW Automotive	Rogersville, TN	PCE	Industrial	TDEC-DSF	Reduce VOC concentrations	Pilot	NA	Closure monitoring	NA
Hanscom AFB	Bedford, MA	TCE, DCE, VC	Air Force	NA	Technology demonstration	Pilot	October 2000	Ongoing	Liles, D. S., 2002
Vandenberg AFB	Lompoc, CA	TCE	Air Force	NA	Technology demonstration	Pilot	February 2001	Ongoing	NA
Ohio Industrial Site	Southwestern Ohio	PCE, TCE	Industrial	State of Ohio	Plume restoration by reactive barrier	Full	1999	Ongoing remediation	Payne et al., 2001
Manufacturing Facility	Southeast England	TCE	Industrial	NA	Plume restoration, partially underneath the facility	Full	1999	Ongoing remediation	Arcadis, 2002
Former Manufacturing Facility	North Carolina	PCE, TCE	Industrial	NA	Technology Demonstration	Pilot	2001	Pilot test process monitoring is ongoing	Shetty and Doucette, 2002
Butyrate									
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	TCE, DCE, VC	Navy	USEPA	Treatability study	Microcosms, Pilot	June 1999	Demonstration Completed	NATO, 2000; AFRL et al., 2001
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	TCE, DCE	Army	NA	Treatability study	Microcosms, Pilot	August 2000	Demonstration Completed	AFRL et al., 2001
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	PCE, TCE	Marine Corps	NA	Treatability study	Microcosms, Pilot	June 2001	Demonstration Completed	AFRL et al., 2001

TABLE 4.1 SUMMARY LISTING OF PHASE I SURVEY SITES (Continued)

Site Name (Sorted by Substrate)	Site Location	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Project Status/ Follow-up	References
Acetate									
Hanford 200 Area Site	Richland, WA	CT, Nitrate	DOE	NA	Technology demonstration	Pilot	January 1995 to March 1996	Demonstration Completed	DOE, 1999
Gillette Company Site	Eastern US	TCE	Industrial	MA DEP	Technology demonstration	Pilot	NA	NA	Chang et al., 2002
Manufacturing Facility	NJ	PCE, TCE	Industrial	NA	Technology demonstration	Pilot	1998	NA	Lipson, D. S., and Persico, J. L., 2002
Methanol/Acetate									
Building 360, Kelly Air Force Base	South Central TX	PCE, TCE, DCE	Air Force	TNRCC	Technology demonstration/ source reduction	Bench, Pilot	December, 1999	NA	Newell et al., 2002; Major et al., 2001
Rademarkt Site	Groningen, Netherlands	PCE, TCE, DCE, VC	Industrial	NA	Technology Demonstration	Pilot	NA	NA	Langenhoff et al., 2001
Lactose									
Former Municipal Waste Water Treatment Facility (Lactose)	NH	PCE, TCE, TCA	Industrial	New Hampshire DES	Groundwater remediation to potable water standards	Full	Pilot: 1997 Full: 2000	Full scale in progress (scheduled until 2003)	Schaffer et al., 2001
Fructose									
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	TCE	Navy	Tennessee DEC, USEPA	Feasibility test for groundwater restoration	Pilot	March 2000	Pilot test complete with continued monitoring, Currently preparing CMS	Britto et al., 2002
Sodium Benzoate									
New England Super Fund Site	New England	DCE, Tetrahydrofuran, Fuel Hydrocarbons	Industrial	NA	Technology demonstration for enhanced bioremediation as a cost effective alternative to pump and treat	Pilot	January 1998	NA	Turpie et al., 2000
Ethanol									
Sages Drycleaner	Jacksonville, FL	PCE DNAPL	Industrial	Florida DEP	Technology Demonstration to remove PCE DNAPL	Pilot	June 1998	Pilot test completed / NA	Jawitz et al., 2000
SEMI- OR SLOWLY-SOLUBLE SUBSTRATES									
HRC™									
Contemporary Cleaners	Orlando, FL	PCE, TCE, DCE, VC	Industrial	Florida DEP	Groundwater remediation via accelerated anaerobic biodegradation	Full	36161	Ongoing	State Coalition for Remediation of Drycleaners (Orlando, FL); Kean et al., 2000, Lodato et al., 2000; Kean et al., 2002; Regenesis Case History #H 1.4 and 1.8

TABLE 4.1 SUMMARY LISTING OF PHASE I SURVEY SITES (Continued)

Site Name (Sorted by Substrate)	Site Location	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Project Status/ Follow-up	References
HRC^{TM} (Continued)									
Decorah Shopping Center Drycleaners	Decorah, WI	PCE	Industrial	Wisconsin DNR	Contaminant source removal, plume stabilization, groundwater restoration	Full	1999	Ongoing	State Coalition for Remediation of Drycleaners (Decorah, WI)
Dixie Cleaners	Jacksonville, FL	PCE, TCE, DCE, VC	Industrial	Florida DEP	Source zone remediation	Pilot	36617	Ongoing, Scale-up to Full Scale	State Coalition for Remediation of Drycleaners (Jacksonville, FL); Murray et al., 2001, Watts et al., 2002
Dover Park Plaza Drycleaning Facility	Yardville, NJ	PCE, DCE	Industrial	NJDEP	Source zone and plume remediation	Pilot, Full	36312	Performance monitoring	Koenigsberg et al., 2000; North et al., 2001
Former Industrial Filter Manufacturer	Rochester, NY	TCE	Industrial	NYSDEC	Polish source area after removal of 2-Phase extraction system	Full	August 1998	Conditional Closure	Boyle, et al., 2000; Case et al., 2001
Former Landfill Site 7, Duluth International Airport	Duluth, MN	TCE	Industrial	Minnesota PCA	Determine potential for groundwater remediation via anaerobic biodegradation	Pilot	April 2000	Ongoing monitoring, Full-scale	Semer and Banerjee, 2001
Watertown Industrial Area	Watertown, MA	PCE, TCE	Industrial	Massachusetts DEP	Feasibility study for enhanced anaerobic biodegradation	Pilot	February 1998	Pilot Completed	Dooley et al., 2000 Murray et al., 2000, Murray et al., 2001
Former Manufacturing Site	Walled Lake, MI	DCE, VC	Industrial	Michigan DEQ	Feasibility study for enhanced anaerobic biodegradation	Pilot	January 1999	Ongoing	Murray et al., 2000, Murray et al., 2001
Unocal Wichita	Wichita, KS	PCE	Industrial	Kansas DEP	Feasibility study for enhanced anaerobic biodegradation	Pilot	September 1999	Ongoing	Murray et al., 2000, Murray et al., 2001; Koenigsberg et al., 2001
FMC Corporation Site	San Jose, CA	TCE	Industrial	California RWQCB	Accelerate groundwater restoration	Pilot/Full	June 1999/May 2000	Ongoing	Zahiraleslamzadeh and Bensch, 2000
Hayden Island Cleaners	Portland, OR	PCE	Industrial	Oregon DEQ	Accelerate groundwater restoration	Full	May 1999	Ongoing	State Coalition for Remediation of Drycleaners (Orlando, FL); Anderson et al., 2000
Naval Air Station Dallas	Dallas, TX	PCE, TCE	Navy	USEPA	Groundwater remediation	Pilot	July 2000	Performance monitoring	CH2M Hill Constructors, 2001
Naval Air Warfare Center	Indianapolis, IN	TCE, DCE	Navy	EPA, IDEM	Groundwater remediation	Full	NA	Ongoing	NA
Hurlburt Field	Tallahasse, FL	TCE, DCE	DoD	USEPA	Accelerate natural attenuation of groundwater to less than 5 years	Pilot	January 1999	Performance monitoring	Harms et al., 2000 Regenesis Case History #H 1.3

TABLE 4.1 SUMMARY LISTING OF PHASE I SURVEY SITES (Continued)

Site Name (Sorted by Substrate)	Site Location	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Project Status/ Follow-up	References
HRC™ (Continued)									
Industrial Site	NJ	PCE	Industrial	NA	NA	Pilot	NA	NA	Koenigsberg et al., 2000; Koenigsberg et al., 2001
Closed Industrial Facility	CO	PCE, TCE	Industrial	Colorado DPHE	Feasibility study	Pilot	September 1999	Ongoing	South et al., 2001
Site 1, Santa Clara County	Santa Clara County, CA	PCE, TCE	Industrial	Regional Water Quality Control Board - SF	Accelerate groundwater restoration	Pilot, Full	December 1999/September 2001	Pilot Completed, expanded application in September 2001	Sharma et al., 2001
Site 2, Santa Clara County	Santa Clara County, CA	PCE, TCE, DCE	Industrial	Regional Water Quality Control Board - SF	Accelerate groundwater restoration in source area	Pilot, Full	October 2000/June 2001	Pilot and expanded test completed	Sharma et al., 2001
Tosco Manufacturing Facility	Burien, WA	PCE, TCE, DCE	Industrial	Washington DEQ	Accelerate groundwater restoration at hotspots	Full	August 2000	Ongoing	Regenesis Case History #H 3.1
Strip Mall Dry Cleaner	Kent, WA	PCE, TCE	Industrial	Washington DEQ	Groundwater remediation	Full	December 1998	No-Further Action Letter	Regenesis Case History #H 2.8
Dayco Manufacturing Facility	Eldora, IA	TCE	Industrial	Iowa DEP	Feasibility study for HRC in a barrier configuration	Pilot	February 1998	Ongoing	Sheldon and Armstrong, 2000; Sheldon and Armstrong, 2002
Moen Manufacturing Facility	Elyria, OH	DCE, VC	Industrial	Ohio DEQ	Feasibility study to compare anaerobic and aerobic degradation of DCE and VC	Pilot	July 1999	Ongoing, full-scale application was planned.	Cornuet, et al., 2000
Springdale Drycleaners	Portland, OR	PCE, TCE	Industrial	Oregon DEQ	DNAPL and source area remediation	Pilot	December 1999	Scheduled full scale HRC application in the fall of 2001	State Coalition for Remediation of Drycleaners (Springdale, OR); Parrett K. and Sandefur C. A., 2002
Reichhold Chemicals	Tacoma, WA	Chlorinated Phenols	Industrial	NA	Groundwater remediation	Pilot	NA	NA	Regenesis Case History #H 2.2
Acton Mickelson Ordinance Facility	Hollister, CA	Perchlorate, Hexavalent Chromium, Freon-113	Industrial	California RWQCB	Groundwater remediation of perchlorate	Full	December 2000	Ongoing	Regenesis Case History #H 2.1
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	2,4,6-trinitrotoluene (2,4,6-TNT), 1,3,5-trinitrobenzene (1,3,5-TNB), 2,4-dinitrotoluene (2-4,DNT), hexahydro-1,3,5-tritro-1,3,5-triazone (RDX)	DoD	Colorado DPHE, USEPA	Groundwater remediation, plume containment	Pilot	February 2000	Below MCLs	Regenesis Case History #H 2.0

TABLE 4.1 SUMMARY LISTING OF PHASE I SURVEY SITES (Continued)

Site Name (Sorted by Substrate)	Site Location	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Project Status/ Follow-up	References
HRC™ (Continued)									
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	TCE	DoD	Colorado DPHE, USEPA	Groundwater restoration	Pilot	February 2001	Ongoing	Schankweiler *et al*., 2002
Manufacturing Facility	Crozet, VA	TCE	Industrial	Virginia DEQ	Feasibility study for a bedrock site	Pilot	December 1999	Below MCLs	Regenesis Case History #H 1.7
Manufacturing Facility	NJ	TCE	Industrial	New Jersey DEQ	Feasibility study	Pilot	NA	NA	Regenesis Case History #H 1.5
Flemington Manufacturing Facility	Flemington, NJ	PCE, TCE, DCE	Industrial	New Jersey DEQ	Feasibility study	Pilot	March 2001	Ongoing	Regenesis Case History #H 1.6; Kozar et al., 2002
Japanese Electrical Plant	Japan	PCE, TCE, DCE	Industrial	NA	Groundwater remediation	Pilot	2000	1 year pilot test was completed.	Nakashima M. and Nishigaki M., 2000
Coopervision Manufacturing Facility	Scottsville, NY	1,1,1-TCA	Industrial	New York State Department of Environmental Conservation	Groundwater remediation	Pilot	July 2001	Injection attempts using direct push failed, mud rotary drilling was used	Case et al., 2001; Dick et al., 2002
Invensys Control	Old Saybrook, CT	PCE	Industrial	Connecticut Department of Environmental Protection	Groundwater restoration to facilitate property transfer	Pilot, Full	Pilot - December 1999 Full - September 2000	Following the success of the pilot test a full scale system was designed by Earth Tech and approved by CTDEP. The full scale was implemented in September 2000	Skoff, et al., 2002
Manufacturing Facility	Brighton, NY	TCE	Industrial	NA	Groundwater Restoration	Pilot	NA	NA	Regenesis Case History #H 1.2
Arlington Cleaners	Arlington, TX	PCE, TCE, DCE, VC	Industrial	TNRCC	Groundwater remediation under voluntary cleanup program	Full	May 2000	Conditional closure under TNRCC	Railsback et al., 2002
Edible Oils									
Former Zipper Manufacturing Facility	Newport News, VA	PCE, TCE, DCE	Industrial	Virginia DEQ	Risk-based closure	Pilot	April 2000	Evaluate full-scale remediation	Skladany et al., 2001
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	PCE, TCE, VC	Air Force	Florida DEP, EPA	Technology demonstration	Pilot, Full	Pilot - June 1999 Full - July 2000	Performance monitoring	Parsons, 2002d
Site N-6, Former NSA Mid-South	Millington, TN	TCE, DCE, CT	Navy	Tennessee DEC and EA	Field feasibility study	Pilot	August 2000	Performance monitoring	Parsons, 2002e
Site SS-015, Travis AFB	Travis AFB, CA	PCE, TCE	Air Force	California RWQCB	Technology demonstration	Pilot, Full	Pilot - April 1999 Full - December 2000	Performance monitoring	Parsons, 2002c
Site FF-87, Former Newark AFB	Newark, OH	PCE	Air Force	Ohio EPA	Accelerate groundwater restoration	Full	September 2001	Performance monitoring	Parsons, 2002a
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	PCE, TCE, VC	Navy	MPCA, EPA - Discharge to Surface Water	Field feasibility study	Pilot	November 2001	Performance monitoring	Parsons, 2001
Former Radiator Facility	IL	TCE	Industrial	NA	Field feasibility study	Pilot	September 2000	Pilot test complete	Parsons, 2002b

TABLE 4.1 SUMMARY LISTING OF PHASE I SURVEY SITES (Continued)

Site Name (Sorted by Substrate)	Site Location	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Project Status/ Follow-up	References
Edible Oils (Continued)									
Site SS-17	Altus AFB, OK	TCE, DCE	Air Force	Oklahoma DEQ, EPA	Field feasibility study	Bench, Pilot	November 2001	Performance monitoring	Terra Systems, 2002
OU-1 Landfill 3	Altus AFB, OK	TCE, DCE	Air Force	Oklahoma DEQ, EPA	Field feasibility study	Pilot	November 2001	Performance monitoring	Terra Systems, 2002
Whiteman Air Force Base LF-08	Whiteman AFB, MO	TCE, DCE, VC	Air Force	Missouri Department of Natural Resources	Field feasibility study	Pilot	July. 2002	Performance monitoring	Parsons, 2002f
SOLID SUBSTRATES									
Bark Mulch									
Building 301, Offutt AFB	Omaha, NE	TCE	Air Force	Nebraska DEQ, EPA	Field feasibility study to accelerate groundwater restoration	Pilot, Full	Pilot: January, 1999 Full: July, 2001	Performance monitoring	Haas et al., 2000; Groundwater Services, Inc., 2001
OU1 Landfill 3	Altus AFB, OK	TCE, DCE	Air Force	Oklahoma DEQ, EPA	Full-scale application to prevent surface water discharge and prevent potential off-base migration	Full	July 2002	Performance monitoring	NA
Naval Weapons Industrial Reserve Plant	McGregor, Texas	Perchlorate	Navy	TNRCC	Ground water restoration for offsite migration via a permeable reactive biobarrier	Bench, Pilot, Full	2000	Performance monitoring	Cowan, 2000
Chitin									
Distler Brickyard Superfund Site	Louisville, KY	TCE, cis-1,2-DCE, VC	Industrial	EPA Region 4	Groundwater remediation to potable water standards	Pilot	October, 2001	Performance monitoring	Sorenson et al., 2002
HYDROGEN									
Gaseous Hydrogen Injection									
Launch Complex 15	Cape Canaveral, FL	PCE, TCE	Air Force	Florida DEP, EPA	Technology demonstration	Pilot	February 1999	Completed pilot test	Newell et al., 2000, 2001, and 2002
Offutt AFB	Omaha, NE	DCE	Air Force	Nebraska DEQ, EPA	Technology demonstration	Pilot	November 1998	Complete	Newell et al., 2000
Twin Cities Army Ammunition Plant	New Brighton, MN	TCE	Army	Non-Regulatory	Technology demonstration for use of hollow fiber membranes to deliver hydrogen in situ	Bench, Pilot	August 2000 (first membrane installation)	Pilot complete, Evaluating field transition plan	Novak et al., 2002

[a/] NA indicates the data are not available.

- Several sites (molasses and HRC™ applications) have either been confirmed as closed, are approved for conditional closure, or have been approved for post-closure monitoring by the governing regulatory agency. ARCADIS (2002) reports three site closures: one with closure based on achieving MCLs, one with a no-further-action decision, and one conditional closure. Overall, Regenesis (Koenigsberg, 2002) reports 18 site closures: 12 sites closed based on achievement of MCLs, 1 site closed with a no-further-action decision, and 5 sites with some form of conditional closure.
- The majority of sites are still under evaluation. This is likely due to the fact that the majority of applications have occurred during the past 2 to 3 years, and the time-frame to determine the effectiveness of enhanced bioremediation is on the order of months to years.

Discussion of the different substrate applications is facilitated by presentation of the survey results in four additional tables. Table 4.2 presents survey data related to site hydrogeological characteristics, Table 4.3 summarizes groundwater contaminant data, Table 4.4 summarizes geochemical data, and Table 4.5 summarizes the substrate remedial design parameters employed. Summary data for these tables are derived from the site survey database, which is provided in Appendix B.

4.1 DISSOLVED PHASE SUBSTRATES

In general, dissolved substrates are composed of organic fatty acids, sugars, and alcohols. The most common dissolved substrates deployed at survey sites are lactate in the form of sodium lactate or lactic acid (14 sites), and molasses (15 sites). Butyrate (or butyric acid) was applied at three sites, acetate at three sites, a methanol/acetate combination at two sites, and sodium benzoate, fructose, lactose, and ethanol were each applied at one site.

4.1.1 Organic Fatty Acids (Lactate, Butyrate, Acetate)

The most common dissolved organic fatty acid substrate used to stimulate anaerobic dechlorination is lactate, in the form of dissolved sodium lactate or lactic acid. As discussed in Section 3, lactate is generally degraded to the secondary fermentation products propionate and acetate. Secondary fermentation of propionate and acetate produces hydrogen, which is used directly as an electron donor for anaerobic dechlorination. While the direct use of propionate has been studied in the laboratory, direct field application of this organic acid was not encountered in the survey.

Lactate was used to stimulate anaerobic dechlorination at a total of 14 sites incorporated into the survey. Eight of these sites are privately-owned industrial sites, with the remainder owned by various Government agencies (DoD and DoE). The use of lactate at 11 of the 14 sites began as pilot-scale applications to demonstrate the effectiveness of this technology. The remaining three sites were started as full-scale applications with specified remedial objectives to reduce contaminant mass within saturated soil and groundwater.

TABLE 4.2 SUMMARY OF HYDROGEOLOGICAL DATA

Site Name (Sorted by Substrate)	Site Location	Lithologic Description	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)
Lactate									
Bachman Road Residential Well Site	Oscoda, MI	Relatively uniform glacial outwash sands and gravels approximately 17 feet thick and underlain by a thick, dense clay unit. The sand and gravel unit is a fining upward sequence with the gravel beds present immediately above the clay unit interface.	NA	8	Unconfined sandy gravel aquifer perched above a dense clay aquitard.	16 - 150	NA	NA	1800
Area 6, Dover AFB	Dover AFB, DE	Sand with varying amounts of clay, silt and gravel. Fine-grained clay and silt to 5-feet bgs underlain by more permeable layer of silt and sand.	NA	10 - 12	Unconfined aquifer made of 3 zones; groundwater occurs in bottom 2 zones of medium sand. Saturated thickness is 38 ft.	60	0.001	30	140
Former Drycleaning Facility	WI	20-feet of glacially deposited sand and gravel overlying sandstone bedrock	NA	10	Unconfined aquifer of glacial deposits, 20 ft thick. Surficial weathered bedrock is also impacted.	0.37 - 4.5	NA	NA	NA
Test Area North (TAN), INEEL	ID	Fractured basalt bedrock. Waste water was injected between 200 and 475 feet below ground surface. The fractured basalt sill is bounded on the bottom by a thick silty aquitard.	NA	200	Impacted fractured basalt aquifer from about 200 ft to about 475 ft bgs.	NA	NA	NA	NA
Ogallala Superfund Site	Ogallala, NE	Approximately 26 to 27 feet of fine to medium grained sand underlain by calcareous silty clay.	NA	11 with season fluctuations to 2	Unconfined aquifer perched above the Ash Hollow silty clay.	450 - 612	0.002	35 - 35	1,095 - 1,280
NAS Fallon	Fallon, NV	Approximately 4-feet of sandy soil underlain by approximately 2-feet of clay-rich silts and sands. Bottom is sandy silt, and clay layer greater 20 feet thick.	NA	8 - 10	Shallow, unconfined, perched aquifer.	NA	0.0004	NA	NA
Former PEC Industries Site	Orlando, FL	The surficial aquifer consists of three sand units separated by sandy clay and clayey sand aquitards. The upper most sand unit extends from ground surface to approximately 10 to 15 feet below ground surface. The remaining two sand units and the intervening sandy	NA	30 - 35	Primary contamination occurs in confined intermediate zone. Pumping to enhance flow in the unit.	NA	NA	NA	NA
Cape Canaveral Facility 1381	Cape Canaveral, FL	Poorly sorted coarse to fine sands and shell material to 35 feet. From 35-50 ft bgs, the sands show a decrease in grain size and silt and clay content increases. A continuous clay unit is present from 48 - 51 ft bgs.	NA	4 - 7	Unconfined aquifer 35 ft thick.	88.7	NA	NA	77

TABLE 4.2 SUMMARY OF HYDROGEOLOGICAL DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Lithologic Description	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)
Lactate (Continued)									
Watertown Industrial Area	Watertown, MA	Industrial site adjacent to river, 20 ft of silty sand on top of thin till and bedrock	NA	8 - 12	Unconfined aquifer.	0.00006	NA	NA	0.005
Aerojet Superfund Site	CA	NA	NA	NA	NA	NA	NA	NA	NA
Naval Air Station Point Mugu IRP Site 24	CA	The upper unconfined aquifer consists of approximately 10 feet of sand and gravel overlying approximately 4 feet of clay. The lower confined aquifer consists of a massive sand unit underlying the clay unit.	NA	5	Shallow unconfined aquifer underlain by a thin but continuous aquitard and a large confined aquifer.	NA	0.001	NA	NA
Weyerhauser Sycan Maintenance Shop	Beatty, OR	The unconfined aquifer matrix consists of sandy silt to a depth of approximately 9 feet below ground surface. Underlying the upper sandy silt is a silty clay aquitard approximately 10 feet thick. The lower aquifer matrix consists of approximately 15 feet of silty sand underlying the upper aquitard and overlying the massive clays of the lower aquitard.	NA	4	Upper perched aquifer overlying a thick and continuous silty clay aquitard. Lower aquifer confined by the upper aquitard and bottomed by the dense clays of the lower aquitard.	NA	NA	NA	NA
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	NA	NA	3	Shallow surficial aquifer which discharges to a nearby surface water body.	NA	NA	NA	NA
Southern US Industrial Site	Unknown	PCE	Industrial	NA	Groundwater remediation	Full	March 1998	Sami Fam Innovative Engineering Solutions Inc.	Ongoing
Molasses									
Avco Lycoming Superfund Site	Williamsport, PA	Glacial sandy silt overburden (25') overlying fractured limestone bedrock	NA	10 - 15	Contaminated aquifer 10-12' thick	0.2 - 24	NA	NA	7.3 to 840
Cedarburgh Drycleaners	Cedarburgh, WI	Poorly drained silty clay topsoil with little sand and gravel (1-4') Silty clay and clayey silts (4-16') Silty clay with trace sand and gravel (15-39') overlying silty find sands	NA	3 to 5	NA	28 (clean, silty sand) 0.03 (silt, silty clay)	0.03 - 0.06	NA	NA
Industrial Site	Central Ohio	Sand and gravel	NA	11	Shallow unconfined aquifer	110	0.02	NA	NA
Washington Square Mall	Germantown, WI	Approximately 14 feet of clay and silt overlying a 2 to 5 foot thick saturated silt and sand bed, clay till aquitard below the saturated silt/sand bed	NA	12 to 14	Groundwater occurs within the 2 to 5 foot thick silt/sand bed at a depth of approximately 14 to 19 feet bgs	0.06	NA	NA	NA

TABLE 4.2 SUMMARY OF HYDROGEOLOGICAL DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Lithologic Description	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)
Molasses (Continued)									
Manufacturing Facility	Greenville, SC	Silty sand and sandy silt (saprolite) overlying a highly weathered transition zone. Bedrock consists of mostly granitic gneiss and schist.	375	22 - 34'	All zones	saprolite: 0.622 transition: 1.44 bedrock: 0.728	-0.63	saprolite: 0.3 bedrock: 0.05	saprolite: 30 bedrock: 200
Crestwood Site	Glendale, WI	Approximately 4 to 12 feet of fill material overlying 4 to 8' of sand; clay till aquitard underlies the sand bed.	NA	6 to 10	Unconfined aquifer	NA	NA	NA	37 to 110
Emeryville Manufacturing Facility	Emeryville, CA	Interbedded sand and clay to a depth of 24 feet underlain by impermeable clay	NA	3.5 - 8'	Unconfined aquifer	NA	NA	NA	60
Manufacturing Facility	Northeastern USA	10-20' thick overburden of glacial sands, silts and clays; water table in underlying bedrock.	NA	25 - 30'	Bedrock aquifer	0.14 to 1.78	NA	NA	10 - 70
Nuclear Fuel Services Site	Erwin, TN	0-30' Alluvial silts, clays, clayey sand, sand w/ gravel and cobbles underlain by weathered, fractured, steeply	NA	4	Unconfined aquifer	0.18	NA	NA	62
TRW Automotive	Rogersville, TN	0-30' Alluvial silts, clays, clayey sand, sand w/ gravel and cobbles underlain by weathered, fractured bedrock	NA	22	Unconfined aquifer	0.0017	NA	NA	0.62
Hanscom AFB	Bedford, MA	Upper and lower aquifers consisting of glacial till overburden overlying bedrock and separated by a stiff,	<529 to 1900	4 to 8	Study focuses on lower, confined aquifer	26	0.006	NA	292
Vandenberg AFB	Lompoc, CA	Alluvial marine sands (with gravel, silt, and clay) over siltstone	<648	13'	Unconfined sand aquifer	1	0.041	NA	40 - 168
Ohio Industrial Site	Southwestern Ohio	Porous, high carbonate aquifer	NA	NA	Unconfined, high carbonate aquifer	NA	NA	NA	360
Manufacturing Facility	Southeast England	Sandy gravel alluvium overlying a thick regional aquitard known as the London Clay	NA	20	Unconfined sandy gravel aquifer	260	NA	NA	1000
Former Manufacturing Facility	North Carolina	Silty clay	NA	NA	Unconfined silty clay aquifer	NA	NA	NA	2.6 - 11.2
Butyrate									
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	NA	NA	4.4 to 6.5	Unconfined shallow with low groundwater velocity	0.006 to 0.019	NA	NA	11.4
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	NA	NA	10	Unconfined	NA	NA	NA	91 to 274
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	Sand and clay sediments to 75 ft bgs. A series of sand and limestone beds occur between 50 and 300 ft bgs, associated with the Castle Hayne Aquifer (CHA).	NA	NA	Unconfined surficial aquifer up to about 50 ft bgs. Receptors include the CHA, which is the principal water supply for the base.	0.4 - 30	NA	NA	NA

TABLE 4.2 SUMMARY OF HYDROGEOLOGICAL DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Lithologic Description	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydrualic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)
Acetate									
Hanford 200 Area Site	Richland, WA	Unsaturated zone extends to a depth of 250 feet. Two permeable zones are located at 250 to 256 feet bgs and 285 to 302 feet bgs with a competant aquitard between.	NA	250	Unconfined high permeability aquifer perched by a 30 aquitard. Confined aquifer lies beneath the aquitard and extends to approximately 302 feet bgs.	high	NA	NA	NA
Gillette Company Site	Eastern US	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	NJ	Thin saturated soil over fractured basaltic bedrock	NA	NA	unconfined overburden aquifer over a fractured bedrock aquifer.	NA	NA	NA	NA
Methanol/Acetate									
Building 360, Kelly Air Force Base	South Central TX	20 to 40 feet of alluvial gravel, sand, and silt overlying impermeable clay.	NA	5 to 10	Unconfined aquifer at 5 to 10 feet bgs	NA	NA	NA	1095
Rademarkt Site	Groningen, Netherlands	NA	NA	NA	NA	NA	NA	NA	NA
Lactose									
Former Municipal Waste Water Treatment Facility (Lactose)	NH	Upper fine sand and silt unit (5-20'); Lower sandy and silt unit (30-50' bgs); aquitard generally extends from 20 to	NA	5 to 10	Shallow unconfined upper hydrogeologic unit with a semi-confined lower	0.28 to 2.8	0.001	NA	NA
Fructose									
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	Fluvial deposits aquifer	<25	47 - 79	Unconfined to semi-confined aquifer 80 to 100 feet thick	44 to 68	0.004	27 (est.)	45 (upper) 22 (lower)
Sodium Benzoate									
New England Super Fund Site	New England	DCE, Tetrahydrofuran, Fuel Hydrocarbons	Industrial	NA	Technology demonstration for enhanced bioremediation	Pilot	January 1998	Craig Lozolte, Envirogen Inc.	NA
Ethanol									
Sages Drycleaner	Jacksonville, FL	PCE DNAPL	Industrial	Florida DEP	Technology Demonstration to remove PCE DNAPL	Pilot	June 1998	James Jawitz, University of	Pilot test completed / NA
SEMI- OR SLOWLY-SOLUBLE SUBSTRATES									
HRC™									
Contemporary Cleaners	Orlando, FL	Fine grained quartz sand (25-30'), clay 1-12'; fine grained sand and sandy clay 20-25'	NA	6 - 8	Unconfined upper surficial aquifer underlain by a thin aquitard and a confined lower	1.3 (upper) 65 (lower)	0.01 (upper) 0.003 (lower)	NA	16 (upper) 2.6 (lower)
Decorah Shopping Center Drycleaners	Decorah, WI	Sandy silt and silty sand with varying amounts of clay (5'), med grained sand (5'-11'bgs) silty sand and sandy silt with silty clay (11-24'bgs), silty clay (24-28'bgs)	NA	6 - 10	NA	3.7	0.028	NA	NA
Dixie Cleaners	Jacksonville, FL	Silty , fine-grained sand (0-18' bgs); clayey fine-grained sand (18-30' bgs); limestone (30-32' bgs)	NA	2	Unconfined aquifer	0.31(shallow sand); 0.23 (clayey sand)	NA	NA	0.00279 (shallow sand) 0.00207 (clay)
Dover Park Plaza Drycleaning Facility	Yardville, NJ	Shallow sand (15-22'), dense silty clay (30')	NA	10	Shallow unconfined aquifer.	14.2	0.007	NA	NA

TABLE 4.2 SUMMARY OF HYDROGEOLOGICAL DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Lithologic Description	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)
HRC™ (Continued)									
Former Industrial Filter Manufacturer	Rochester, NY	Relatively low permeability clayey silts	NA	1 to 2	Unconfined clayey silt aquifer	0.0003 to 0.003	NA	NA	NA
Former Landfill Site 7, Duluth International Airport	Duluth, MN	NA	NA	5 - 6	Receptor one mile from site	NA	NA	NA	18 (surficial aquifer)
Watertown Industrial Area	Watertown, MA	Approximately 13 feet of sand and gravel overlying approximately 7 feet of silty sand. The surficial material is underlain by an aquitard consisting of glacial till.	NA	8 - 12	Unconfined aquifer	NA	NA	NA	NA
Former Manufacturing Site	Walled Lake, MI	Silty sand	NA	NA	NA	NA	NA	NA	NA
Unocal Wichita	Wichita, KS	Silt and clay	NA	5 - 9	NA	NA	NA	NA	0.03
FMC Corporation Site	San Jose, CA	Silty clays (45-50'); gravelly sand (30-35')	NA	7 - 10	Semi-confined aquifer	NA	NA	NA	10
Hayden Island Cleaners	Portland, OR	20-40 feet of silty sand	NA	25	Unconfined aquifer strongly influenced by the stage of the	NA	0.001	NA	NA
Naval Air Station Dallas	Dallas, TX	Fine-grained fill, alluvial sediments, weathered shale	NA	8 - 26	Unconfined aquifer	NA	NA	NA	NA
Naval Air Warfare Center	Indianapolis, IN	NA	NA	0	NA	NA	NA	NA	NA
Hurlburt Field	Tallahasse, FL	The intermediate aquifer consists of sand, silty sand, and discontinuous lenses of clay and is located from 40 to 50 feet below ground surface.	NA	NA	Confined surficial aquifer	NA	NA	NA	128
Industrial Site	NJ	NA	NA	NA	NA	NA	NA	NA	NA
Closed Industrial Facility	CO	20-25' Unconsolidated silt and clay with occasional lenses of fine sand and sandy clay; severely weathered claystone	NA	7 - 10	Impacted aquifer consists of unconsolidated silt and clay, and is 20 to 25 feet thick.	2.4 to 5	NA	NA	183
Site 1, Santa Clara County	Santa Clara County, CA	Interbedded layers of clay, silty sand, and sand (clay is predominant soil type above water-bearing zone)	NA	7 - 10	NA	2.8 to 28	0.001 to 0.002	15	55
Site 2, Santa Clara County	Santa Clara County, CA	Interbedded layers of clay, silty sand, and sand (clay is predominant soil type above water-bearing zone)	NA	7 - 10	NA	28 to 141	0.001 to 0.002	30	1825
Tosco Manufacturing Facility	Burien, WA	NA	NA	5 - 9	NA	NA	NA	NA	0.22
Strip Mall Dry Cleaner	Kent, WA	NA	NA	NA	NA	NA	NA	NA	274
Dayco Manufacturing Facility	Eldora, IA	Stratigraphic consists of approximately 30 feet of dense clay overlying approximately 20 feet of sand. The	NA	NA	Surficial aquifer perched above a silt layer and confined below a dense clay	NA	NA	NA	NA
Moen Manufacturing Facility	Elyria, OH	Approximately 5 to 8 feet of overburden overlying approximately 30 feet of fine to medium grained	NA	9.5 - 11.5	Fractured sandstone bedrock aquifer	4	0.008	15	75

TABLE 4.2 SUMMARY OF HYDROGEOLOGICAL DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Lithologic Description	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)
HRC™ (Continued)									
Springdale Drycleaners	Portland, OR	Sandy , silty, clay from groundsurface to approximately 12 feet below ground surface underlain by approximately 10	NA	20	unconfined surficial aquifer	NA	0.0001	NA	NA
Reichhold Chemicals	Tacoma, WA	Approximately 400 feet of fine grained marine sediments	NA	NA	Unconfined aquifer	NA	NA	NA	NA
Acton Mickelson Ordinance Facility	Hollister, CA	Fine to medium silty sand	NA	NA	Shallow unconfined aquifer	NA	NA	NA	26
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Sand and clayey sand overlain by a clay to silty sand confining or semi-confining unit.	NA	37	Confined surficial aquifer present in the sand and clayey sand unit	NA	NA	NA	18000
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Alluvial aquifer	NA	NA	Alluvial aquifer	NA	NA	NA	1,825 to 18,250
Manufacturing Facility	Crozet, VA	Fractured crystalline bedrock	NA	22 - 32	Bedrock aquifer	NA	NA	NA	NA
Manufacturing Facility	NJ	Yes	TCE	Industrial	New Jersey DEQ	Feasibility study	Pilot	NA	Steve Koenigsberg,
Flemington Manufacturing Facility	Flemington, NJ	NA	NA	NA	NA	NA	NA	NA	NA
Japanese Electrical Plant	Japan	Gravel and cobble aquifer matrix perched above an aquitard. The aquifer	NA	7	Unconfined gravel aquifer	NA	NA	NA	NA
Coopervision Manufacturing Facility	Scottsville, NY	Very dense till consisting of clayey silts and some sand	NA	5	unconfined dense till aquifer	NA	NA	NA	NA
Invensys Control	Old Saybrook, CT	PCE	Industrial	Connecticut Department of Environmental	Groundwater restoration to facilitate property transfer	Pilot, Full	Pilot - December 1999 Full - September	Dale Skoff, Earth Tech, Inc. 724-934-1666	Following the success of the pilot test a full scale system was
Manufacturing Facility	Brighton, NY	TCE	Industrial	NA	Groundwater Restoration	Pilot	NA	Steve Koenigsberg, Regenesis	NA
Arlington Cleaners	Arlington, TX	PCE, TCE, DCE, VC	Industrial	TNRCC	Groundwater remediation under voluntary cleanup program	Full	May 2000	Rick Railsback, ProGEA Inc Dallas, TX 972-	Conditional closure under TNRCC
Edible Oils									
Former Zipper Manufacturing Facility	Newport News, VA	NA	NA	1.5	Shallow coastal plain aquifer, extending from 5' bgs with confining layer at ~10' bgs	0.09 to 1.1	NA	NA	3
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	Sand and silty sand with some shell fragments and organic matter to 35' bgs, clay layer at 36 to 42 feet bgs	NA	4 - 6	Unconfined aquifer 30 to 35 feet thick	100 to 500	0.0003 to 0.0007	25 (est.)	40 to 500
Site N-6, Former NSA Mid-South	Millington, TN	Fluvial deposits from 40 to 90 feet bgs consisting of sand, silty sand, and clay stringers	<25	47 - 79	Unconfined to semi-confined aquifer 80 to 100 feet thick	44 to 68	0.004	27 (est.)	45 (upper) 22 (lower)

TABLE 4.2 SUMMARY OF HYDROGEOLOGICAL DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Lithologic Description	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydrualic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)
Edible Oils (Continued)									
Site SS-015, Travis AFB	Travis AFB, CA	Silty clay with thin layers of silt and silty sand	NA	8 - 11	Unconfined overburden aquifer approximately 20 to 25 feet thick	0.003 to 0.04	0.003	10 (est.)	0.005 to 0.85
Site FF-87, Former Newark AFB	Newark, OH	Alluvial medium to coarse sand underlain by Pleistocene glacial silty clay	<34 to 2,400	9 - 14	Unconfined aquifer with confining layer at 25 to 30 feet bgs	16 to 22 (upper) 0.016 to 0.24 (lower)	0.015	25 (est.)	403 (upper) 3.1 (lower)
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	Glacial-fluvial medium to coarse grained sand	<500 to 7,100	28 - 34	Shallow unconfined aquifer underlain by a discontinuous clay aquitard at 70 to 93 feet bgs	NA	0.008	25 (est.)	110 to 730
Former Radiator Facility	IL	Clayey sand	NA	5	Shallow unconfined aquifer	NA	NA	NA	NA
Site SS-17	Altus AFB, OK	Reddish brown , moderately plastic, sandy clay to 15 feet below ground surface underlain by clayey shale with occasional gypsum layers.	NA	8 - 10	Unconfined silty clay aquifer	NA	NA	NA	100
OU-1 Landfill 3	Altus AFB, OK	Reddish brown , moderately plastic, sandy clay to 15 feet below ground surface underlain by clayey shale with occasional gypsum layers.	NA	8 - 10	Unconfined silty clay aquifer	NA	NA	NA	100
Whiteman Air Force Base LF-08	Whiteman AFB, MO	Approximately 24 feet of dense clay overlying a clayey gravel zone which extends to the top of weathered claystone bedrock at 30 feet below ground surface.	240 to 710	6	Unconfined clay aquifer. Groundwater flow is predominantly in the clayey gravel interval at 24-28 feet bgs.	0.06 to 0.2	0.016	25	1.4 to 4.9
SOLID SUBSTRATES									
Bark Mulch									
Building 301, Offutt AFB	Omaha, NE	Stiff to very stiff, reddish brown, low plasticity, silty clay	3.0 to 36	6	Shallow unconfined aquifer	3.5	0.01	15	84
OU1 Landfill 3	Altus AFB, OK	Reddish brown silty clay	190 to 320	6 to 12	Shallow unconfined aquifer	8.4 to 43	0.003	10	0.25 to 1.25
Naval Weapons Industrial Reserve Plant	McGregor, Texas	NA	NA	NA	Shallow unconfined aquifer	NA	NA	NA	NA
Chitin									
Distler Brickyard Superfund Site	Louisville, KY	Relatively low permeability silts and clays	NA	Approximately 35	Unconfined aquifer	0.03 to 0.31	NA	10 to 15 (est.)	NA
HYDROGEN									
Gaseous Hydrogen Injection									
Launch Complex 15	Cape Canaveral, FL	Silica sand with some shell fragments containing clay and organic matter to 70 feet bgs	NA	6 to 7	Shallow Unconfined	95	<0.0011	30	124.1
Offutt AFB	Omaha, NE	Sand	3.0 to 35.5	8 to 10	Shallow unconfined aquifer	3.5	0.01	15	84
Twin Cities Army Ammunition Plant	New Brighton, MN	NA	NA	NA	Shallow Unconfined	NA	NA	NA	NA

[a/] NA indicates the data are not available.

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Lactate						
Bachman Road Residential Well Site	Oscoda, MI	Industrialized area - source unknown	TCE - 0.13 DCE - 0.19 VC - 0.25 Ethene - ND	TCE - ND DCE - ND VC - ND Ethene - 0.36	cis-1,2-DCE, VC	Contaminant concentration reduction, as measured in one monitoring well, was nearly 100% for TCE, DCE, and VC.
Area 6, Dover AFB	Dover AFB, DE	Waste disposal facility	PCE - 0.046 TCE - 7.5 DCE - 2 VC - 0.034	PCE - ND TCE - 0.075 DCE - 0.045 VC - 0.020	Arsenic, cadmium	As of March 1998, 98.5% of TCE and DCE in groundwater were converted to ethene and 75% to 80% of the TCE and DCE mass had been recovered as ethene.
Former Drycleaning Facility	WI	Former drycleaning facility	PCE - 0.52 TCE - ND DCE - ND	PCE - 0.22 TCE - 0.003 DCE - 0.028	NA	PCE concentrations were reduced by approximately 58% while TCE and DCE concentrations increased form below method detection limits to concentrations greater than the Federal MCL for each contaminant.
Test Area North (TAN), INEEL	ID	Former wastewater and sanitary sewage injection well	TCE - 3.2	TCE - < 0.005	NA	Within 6 weeks from the start of lactate injection nearly 100% of TCE concentrations in groundwater had been dechlorinated to DCE and complete dechlorination was occurring within 4 months.
Ogallala Superfund Site	Ogallala, NE	NA	PCE - 0.03 TCE - ND DCE - ND VC - ND	PCE - 0.06 TCE - 0.001 DCE - 0.14 VC - NA	NA	Contaminant reduction calculations could not be performed due to the limited availability of analytical data.
NAS Fallon	Fallon, NV	Former open fire-training pit	PCE - 0.680 TCE - 0.915 DCE - 0.866 VC - 0.0043	PCE - <0.025 TCE - ~0.1 DCE - ~0.250 VC - 0.0015	1,1-DCE, Benzene, Toluene	Contaminant concentration reduction in groundwater ranged from a minimum 65% in the case of VC to a maximum of 99.7% in the case of PCE.
Former PEC Industries Site	Orlando, FL	Printed circuit board manufacturer. VOC contamination present beneath a former drum storage area.	PCE - 0.043 TCE - 0.017 DCE - 8.1 VC - 0.112 Ethene - 0.003	NA	1,1-DCE, CA	As of May 2001, substrate injection had not been performed at this site.
Cape Canaveral Facility 1381	Cape Canaveral, FL	Cleaning and degreasing operations at the Ordnance Support Facility.	TCE - 1.97 DCE - 11.1 VC - 1.25 Ethene - < 0.2	TCE - ND DCE - 0.97 VC - 0.625 Ethene - 1.75	NA	RABITT protocol slightly modified because Florida's UIC regulations do not allow for reinjection of contaminated groundwater. Reduction of TCE, DCE, and VC by 88.7%, 90.6%, and 66.3%, respectively

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Lactate (Continued)						
Watertown Industrial Area	Watertown, MA	Former metal degreasing shop	PCE - 1.5 TCE - 12.0 DCE - 3.5 VC - 0.1 Ethene - N/A	PCE - 0.1 TCE - 1.0 DCE - 3.0 VC - 1.0 Ethene - N/A	NA	Contaminant concentration reduction ranged from 7% in the case of PCE to 92% in the case of TCE. Contaminant mass reductions were measured in a single well (IN-2).
Aerojet Superfund Site	CA	Aircraft manufacturing facility, plating	TCE - NA DCE - NA VC - NA Ethene - NA	TCE - < 0.005 DCE - NA VC - NA Ethene - NA	NA	TCE concentrations were reduced by nearly 100% 125 days of injection.
Naval Air Station Point Mugu IRP Site 24	CA	Oil/water separator	TCE - 1.7 DCE - 0.75 VC - 0.001 Ethene - NA	TCE - < 0.005 DCE - < 0.005 VC - 0.015 Ethene - 0.020	NA	Within approximately 180 days TCE and DCE concentrations had been reduced by nearly 100% at one well. However VC concentrations increased by a factor of 15 within the same time period.
Weyerhauser Sycan Maintenance Shop	Beatty, OR	Maintenance facility for railroad cars and engines	PCE - 1.7 TCE - 0.45 DCE - 3.6 VC - 0.09 Ethene - NA	PCE - 0.2 TCE - 0.16 DCE - 1.4 VC - 0.09 Ethene - NA	1,1,1-TCA, Trichlorofluoroethene (TCFE) used as a tracer due its chemical similarities to PCE and TCE	The PCE, TCE, and DCE concentrations were reduced by approximately 88%, 64%, and 61% respectively while the VC concentration stayed about the same.
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	Chemical weapons training	1,1,2,2-PCA - 20 TCE - 1 DCE - ND VC - ND	1,1,2,2-PCA - 3.5 TCE - 1.8 DCE - 3.9 VC - ND	1,1,1-TCA, 1,2-DAC, chloroethane, DCE, VC	Within 14 weeks the 1,1,2,2-PCA concentration at one well was reduced by 83% while the TCE and DCE concentrations increased.
Southern US Industrial Site	Unknown	Industrial Use	NA	NA	NA	Analytical data was not provided for this site.
Molasses						
Avco Lycoming Superfund Site	Williamsport, PA	Aircraft manufacturing facility, plating	TCE - 0.048 DCE - 0.010 VC - < 0.001	TCE - 0.0014 DCE - 0.002 VC - < 0.001	Hexavalent chromium, cadmium	NA
Cedarburgh Drycleaners	Cedarburgh, WI	Drycleaning facility	PCE - 6.8 TCE - 0.810 DCE - 1	NA	1,1-DCE	NA
Industrial Site	Central Ohio	Lagoon area used to contain metal machining liquid wastes	DCE - 0.265 VC - 0.015	DCE - 0.025 VC - 0.004	Fuels and cutting oil constituents	After 6 months of process monitoring, average DCE and VC concentrations had been reduced by 91% and 73% respectively.
Washington Square Mall	Germantown, WI	NA	PCE - 1.5 TCE - 0.1 DCE - < 0.1 VC - ND Ethene - ND	PCE - ND TCE - ND DCE - 0.4 VC - 0.1 Ethene - 0.35	NA	NA

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Molasses (Continued)						
Manufacturing Facility	Greenville, SC	Manufacturing facility	CT = 0.19 - 1.2	Target: 0.005	Chloroform, TCE, PCE, other VOCs	NA
Crestwood Site	Glendale, WI	Former drycleaning facility	PCE - 44.0	NA	NA	NA
Emeryville Manufacturing Facility	Emeryville, CA	Metal plating and degreasing operations	PCE - 0.084 TCE - 6.5 DCE - 0.590 VC - 0.010	PCE - < 0.005 TCE - < 0.005 DCE - < 0.005 VC - 0.021	Hexavalent chromium	NA
Manufacturing Facility	Northeastern USA	Manufacturing facility	PCE - 80 TCE - 1 DCE - 1 VC - ND Ethene - < 0.001	PCE - 0.001 TCE - 0.001 DCE - 0.001 VC - 0.002 Ethene - 1.4 mg/l	NA	NA
Nuclear Fuel Services Site	Erwin, TN	Uranium fuel production facility	PCE - 12.4 TCE - 1.14 DCE - 0.66 VC - 0.13 Ethene - 0.024	PCE - 0.85 TCE - 0.32 DCE - 67.8 VC - 13 Ethene - 1.6	Uranium	Within 6 months following substrate injection PCE, and DCE contaminant mass had been reduced by 93% and 82% respectively. Within the same time period DCE, VC, and ethene concentrations increased by approximately 2 orders of magnitude.
TRW Automotive	Rogersville, TN	Automotive parts manufacturing	PCE - 22 TCE - 0.005 DCE - 0.042 VC - 0.001 Ethene - 0.009	PCE - 0.0022 TCE - < 0.002 DCE - 0.0086 VC - 0.0226 Ethene - 0.024	NA	NA
Hanscom AFB	Bedford, MA	Pyrokinetic training and research	TCE - 1.9 DCE - 5.3 VC - 1.3 Ethene - 0.17	TCE - 1.9 DCE - 5.3 VC - 1.3 Ethene - 0.17	1,1-DCA, 1,1-DCE	Post-treatment concentrations are those from existing monitoring well after 19 months of demonstration testing
Vandenberg AFB	Lompoc, CA	Missile silo	TCE - 4.0	TCE - 0.019	NA	Concentrations from existing monitoring well showing good treatment.
Ohio Industrial Site	Southwestern Ohio	NA	PCE - 0.5 TCE - 0.7 VC - 0.003 Ethene - <0.001	PCE - <0.001 TCE - <0.001 VC - <0.001 Ethene - <0.001	NA	Within approximately 440 days following substrate injection PCE, TCE, DCE, and VC concentrations in groundwater had been reduced by nearly 100%. At day 180 DCE concentrations peaked and began to decline while ethene concentrations peaked at day 240.

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Molasses (Continued)						
Manufacturing Facility	Southeast England	Manufacturing facility	TCE - 22 DCE - 12 VC - 0.045 Ethene - 0.002	TCE - 0.014 DCE - 20.8 VC - 4.5 Ethene - 1.1	Petroleum constituents	Since substrate injection in 1999 the average TCE concentration has decreased by nearly 100% while VC and ethane concentrations have increased by 1 and three orders of magnitude respectively and the average DCE concentration has increased by approximately 73%.
Former Manufacturing Facility	North Carolina	Manufacturing facility	PCE - 11 TCE - 0.18	NA	NA	NA
Butyrate						
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	Former engine testing and repair facility	TCE - 24 DCE - 8.6 VC - 2.2 Ethene - NA	TCE - 0.7 DCE - 2.4 VC - 0.6 Ethene - 2.0	Dichlorobenzene, methylene chloride, toluene, sodium hydroxide	Water injected with amendments contained average TCE, cDCE, and VC concentrations of 81.7 mM, 7.0 mM, and 3.4 mM, respectively. Average TCE concentrations were reduced by 94% by the end of the demonstration.
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	Waste Storage and Disposal Area	TCE - 1.5 to 6.3	TCE - 0.069 DCE - NA VC - 0.217	BTEX	Injected TCE concentrations spiked as high as 169 mg/L, but this did not prove toxic to the microorganisms.
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	Drycleaning operations, leaking underground storage tanks	NA	Average instead of max: PCE - 5.5 TCE - 0.4 DCE - 0.08 VC - < 0.006	NA	NA
Acetate						
Hanford 200 Area Site	Richland, WA	Sanitary tile disposal site for the 221-T plant	CT - Nitrate -	CT - Nitrate -	NA	Approximately 2 kg of CT was reported to have been destroyed during the 14 month pilot test. Within the same time period approximately 30 kilograms (dry weight) of bacterial biomass was produced.
Gillette Company Site	Eastern US	NA	NA	NA	NA	NA
Manufacturing Facility	NJ	Manufacturing facility	NA	NA	NA	NA
Methanol/Acetate						
Building 360, Kelly Air Force Base	South Central TX	Aircraft maintenance and cleaning	PCE - 8.1 TCE - 0.19 DCE - 2.1 VC - ND Ethene - ND	PCE - 0.81 (est.) TCE - 0.019 (est.) DCE - 0.315 (est.) VC -NA Ethene - NA	None	Reported a 90% reduction in PCE. Cis-1,2-DCE degradation was observed only after the addition of the KB-1 microbial consirtium amendment.
Methanol/Acetate (Continued)						

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Rademarkt Site	Groningen, Netherlands	NA	PCE - 1.28 TCE - 1.03 DCE - 2.6 VC - 0.94 Ethene - NA	PCE - 0.60 TCE - 0.01 DCE - 0.29 VC - 2.26 Ethene - NA	NA	Contaminant concentration reductions represent site average concentrations before injection and 25 weeks after injection.
Lactose						
Former Municipal Waste Water Treatment Facility (Lactose)	NH	Sludge disposal pit	PCE - 0.02 TCE - 0.3 DCE - 8.4 VC - 1.5 Ethene - N/A	PCE - < 0.001 TCE - < 0.001 DCE - 2.7 VC - 0.3 Ethene - N/A	NA	NA
Fructose						
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	Aircraft Maintenance Operations	NA	NA	NA	NA
Sodium Benzoate						
New England Super Fund Site	New England	Landfill	NA	NA	Arsenic	Degradation rates were calculated for cis-1,2-DCE and VC based on production rates of ethene and ethane for the first two years of operation. The average half life calculated for cis-1,2-DCE was 255 days. The calculated average half life for VC was 48 days.
Ethanol						
Sages Drycleaner	Jacksonville, FL	Drycleaning facility	PCE - 150	PCE - 44	NA	Approximately 43 liters of PCE were recovered from the extracted water/ethanol waste stream. This PCE mass represents approximately 63% of the total PCE mass present in the flushed area indicating that the extraction efficiency is 63%.
SEMI- OR SLOWLY-SOLUBLE SUBSTRATES						
HRC™						
Contemporary Cleaners	Orlando, FL	Drycleaning facility	PCE - 19.2 TCE - 2.5 DCE - 6.3 VC - 2.4	PCE - 0.82 TCE - 1.3 DCE - 4.0 VC - 1.0	NA	Within 152 days following injection PCE, TCE, DCE, and VC concentrations were reduced by 96%, 48%, 38%, and 58%, respectively, over 5 wells screened in the shallow aquifer.

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
HRC™ (Continued)						
Decorah Shopping Center Drycleaners	Decorah, WI	Drycleaning facility	PCE - 0.018 TCE - 0.0004 DCE - < 0.001	NA	NA	This project has not been implemented as of spring 2002
Dixie Cleaners	Jacksonville, FL	Drycleaning facility	PCE - 5.2 TCE - 12.7 DCE - 7.5 VC - 1.1	PCE - 0.042 TCE - 1.3 DCE - < 0.005 VC - N/A	NA	Average PCE, TCE, and DCE concentrations were reduced by 99%, 90%, and 99% 7 months after injection.
Dover Park Plaza Drycleaning Facility	Yardville, NJ	Drycleaning facility	PCE - 1.4 TCE - 0.02 DCE - 0.1 VC - < 0.005	PCE - < 0.005 TCE - < 0.005 DCE - 0.22 VC - < 0.005	NA	After approximately 400 days following the full scale application PCE and TCE concentrations were reduced by approximately 99% and 75% respectively
Former Industrial Filter Manufacturer	Rochester, NY	NA	TCE - 26 DCE - 0.34 VC - ND Ethene - ND	TCE - 4.7 DCE - 18 VC - 0.19 Ethene - 0.0731	None	Contaminant concentration data used to calculate mass reduction represents maximum values detected in 5 monitoring wells. Within 15 months of injection TCE concentrations were reduced by approximately 64% while DCE and VC concentrations increased by approximately 288% and 3700% respectively.
Former Landfill Site 7, Duluth International Airport	Duluth, MN	USAF Landfill active from the 1950s through the 1970s	TCE - 0.354 DCE - 0.05 VC - 0.01	TCE - ND DCE - 0.7 VC - 0.02	NA	DCE and VC peaked before starting to decline at end of pilot test
Watertown Industrial Area	Watertown, MA	Former metal degreasing shop	PCE - 1.0 TCE - 13.0 DCE - 3.0 VC - 0.2	PCE - 0.0085 TCE - 0.095 DCE - 0.163 VC - < 0.2	DCE	Average PCE, TCE, and DCE concentrations were reduced by 99%, 99%, and 95% at 206 days after injection.
Former Manufacturing Site	Walled Lake, MI	NA	DCE - 9.9 VC - 1.9 Ethene - 1.0	DCE - 5.6 VC - 3.2 Ethene - 0.227	NA	Groundwater results showed large amounts of lactic acid fermentation
Unocal Wichita	Wichita, KS	NA	PCE - 7.0 TCE - 0.84 DCE - 0.56 VC - ND	PCE - 0.04 TCE - 0.54 DCE - 15.0 VC - 1.0	NA	PCE was degraded from 6 mg/L to 0.2 mg/L within 30 days

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
HRC™ (Continued)						
FMC Corporation Site	San Jose, CA	Former heavy manufacturing facility	TCE - 3.62 DCE - 0.21 VC - 0.02 Ethene - 0.24	TCE - 3.15 DCE - 0.55 VC - 0.57 Ethene - 2.0	NA	Contaminant concentrations used to calculate mass reductions represent averages of 6 site wells used to monitor this pilot test. Within 6 months of injection the average TCE concentration had been reduced by 13%. DCE, VC, and ethene concentrations increased by 161%, 2750%, and 733% respectively during the same time period.
Hayden Island Cleaners	Portland, OR	Drycleaning facility	PCE - 0.8 TCE - 0.001 DCE - 0.0034	PCE - 0.2 TCE - 0.035 DCE - 0.070	TCE, DCE	PCE concentrations were reduced by approximately 75% within 20 months of injection, while TCE and DCE concentrations increased within the same time period.
Naval Air Station Dallas	Dallas, TX	Former petroleum, oil, and lubricants yard	PCE - 0.099 TCE - 0.044 DCE - 0.011	PCE - 0.079 TCE - 0.051 DCE - 0.023	NA	NA
Naval Air Warfare Center	Indianapolis, IN	Naval air warfare facility	TCE - 1.0 DCE - 0.202 VC - 0.0003 Ethene - N/A	TCE - 0.54 DCE - ND VC - 0.0005 Ethene - 0.012	NA	NA
Hurlburt Field	Tallahasse, FL	Petroleum, oil, and lubricants yard	TCE - 9.5 DCE - 2.0 VC - < 0.1 Ethene - 0.01	TCE - 1.0 DCE - 8.5 VC - 1.5 Ethene - 0.05	NA	Within 1 year of injection TCE concentrations had decreased by approximately 89% while DCE, VC, and ethene concentrations increased by approximately 325%, 1,400%, and 400% respectively. These concentration changes are representative of one well installed approximately 5 feet downgradient of the injection area. The highest concentrations detected during the baseline event were detected at this well.
Industrial Site	NJ	Industrial site	PCE - 5.28 TCE - 0.227 DCE - 0.01 VC - ND	PCE - 0.775 TCE - 0.866 DCE - 3.353 VC - ND	NA	NA
Closed Industrial Facility	CO	Former industrial facility	PCE - 9.0 TCE - 1.4 DCE - 0.56	PCE - 0.5 TCE - 0.68 DCE - 17.0	NA	Within first month of HRC injection, PCE concentrations decreased by up to 97% in the source zone.

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
HRC™ (Continued)						
Site 1, Santa Clara County	Santa Clara County, CA	Manufacturing facility	PCE - 0.027 TCE - 11.0 DCE - 0.595 VC - < 0.05 Ethene - 0.000026	PCE - < 0.02 TCE - 0.071 DCE - 5.23 VC - 0.014 Ethene - 0.000447	NA	NA
Site 2, Santa Clara County	Santa Clara County, CA	Manufacturing facilities	PCE - 0.22 TCE - 0.82 DCE - 3.0 VC - 0.3 Ethene - 0.021	PCE - 0.023 TCE - 0.94 DCE - 1.516 VC - 1.4 Ethene - 1.2	NA	NA
Tosco Manufacturing Facility	Burien, WA	Manufacturing facility	PCE - 11.4 TCE - 1.7	PCE - 3.1 TCE - 2.5	NA	Within 159 days following injection the PCE concentration in one well was reduced by 73% while the TCE concentration in the same well increased by 44%. DCE and VC data for this site were not provided.
Strip Mall Dry Cleaner	Kent, WA	Drycleaner	PCE - 67.4 TCE - 11.7 DCE - 0.36 VC - .060 Ethene - < 0.005	PCE - 0.034 TCE - 0.017 DCE - 0.02 VC - 0.07 Ethene - < 0.005	NA	PCE and TCE concentrations had been reduced by nearly 100% within 14 months of injection at one source area well. DCE and VC concentrations had been reduced by 44% and 88% respectively in one downgradient well within 2 years of injection.
Dayco Manufacturing Facility	Eldora, IA	Manufacturing facility	TCE - 2.23 DCE - 5.03 VC - 0.134	TCE - 0.56 DCE - 1.71 VC - < 0.001	NA	Within 35 weeks of injection TCE, DCE, and VC concentrations were reduced by approximately 75%, 66%, and nearly 100% respectively. These reductions were observed in one well approximately 5 feet downgradient from the injection well. Contaminant concentration data from wells further downgradient from the injection area were not provided.
Moen Manufacturing Facility	Elyria, OH	Manufacturing facility	DCE - 0.59 VC - 0.21	DCE - 0.02 VC - 0.01	NA	Original COC was TCE but nearly all TCE mass has been reduced naturally to DCE and VC. TCE has not been detected onsite at concentrations exceeding the MCL for several years. Within 180 days of injection DCE and VC concentrations in one well 25 feet downgradient from the injection area were reduced by approximately 97% and 94% respectively.

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
HRC™ (Continued)						
Springdale Drycleaners	Portland, OR	Drycleaner	PCE - 98 TCE - 35.9 DCE - < 0.005 VC - < 0.005 Ethene - NA	PCE - < 0.25 TCE - 0.30 DCE - 43.9 VC - 9.5 Ethene - NA	Cis-1,2-DCE, trans-1,2-DCE, VC	Within 18 months after the pilot scale injection PCE and TCE concentrations had decreased by 99% while DCE and VC concentrations had increased significantly in one well installed an
Reichhold Chemicals	Tacoma, WA	Pentachlorophenol and treated fiber product plant	Pentachlorophenol - 1.6 2,3,4,6-Tetrachlorophenol - 0.2 2,4,5-Trichlorophenol - < 0.05 2,4-Dichlorophenol - < 0.05	Pentachlorophenol - 0.54 2,3,4,6-Tetrachlorophenol - 0.1 2,4,5-Trichlorophenol - < 0.05 2,4-Dichlorophenol - < 0.05	Aroclor-1248, molybdenum, lead	Within 280 days after injection PCP and 2,3,4,6-TCP concentrations had been reduced by approximately 66% and 50% respectively at one monitoring well installed approximately 10 downgradient from the line of injection wells.
Acton Mickelson Ordinance Facility	Hollister, CA	Ordinance production plant	Perchlorate - 7.5 Chrome-6 - 0.16 Freon-113 - 0.25	Perchlorate - 1.0 Chrome-6 - < 0.1 Freon-113 - 0.02	NA	Within 80 days after injection perchlorate, hexavalent chromium, and freon-1113 concentrations had been reduced by approximately 87%, nearly 100%, and 92% respectively at one well installed within the injection grid. No analytical data was provided for wells installed downgradient from the injection area.
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Explosives and ordinance production	2,4-DNT - 0.0037 RDX - 0.0093 1,3,5-TNB - 0.231 Hydrazine - 0.001	2,4-DNT - 0.0003 RDX - < 0.0001 1,3,5-TNB - 0.005 Hydrazine - NA	Nitrate, Hydrazine	Within approximately 105 days following injection 2,4-DNT, RDX, and 1,3,5-TNB concentrations had decreased by approximately 89%, 99%, and 98% respectively. These reduction calculations represent average concentrations calculated from 4 downgradient monitoring wells. Concentration data was provided for only the 4 wells closest to the injection area (approximately 30 feet downgradient) out of a total of 15 monitoring wells used for process monitoring.
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	NA	NA	NA	NA	Contaminanat data was minimal during irst 3 months of pilot test. However, and order of magnitude reduction in TCE concentration was observed 50 feet downgradient of treatment zone after 11 months.

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
HRC™ (Continued)						
Manufacturing Facility	Crozet, VA	Manufacturing facility	TCE - 0.225 DCE - 0.125 VC - < 0.005 Ethene - < 0.005	TCE - < 0.005 DCE - 0.08 VC - 0.05 Ethene - 0.05	NA	Within 13 months of injection TCE and DCE concentrations had decreased by approximately 98% and 94% respectively while VC and ethene concentrations had increased by approximately 900% in one monitoring well installed approximately 10 feet downgradient from the injection wells.
Manufacturing Facility	NJ	Manufacturing facility	NA	NA	NA	Contaminant concentration data was not provided.
Flemington Manufacturing Facility	Flemington, NJ	Manufacturing facility	PCE - .011 TCE - 0.10 DCE - 0.05 VC - NA Ethene - NA	PCE - 0.004 TCE - 0.009 DCE - 0.022 VC - NA Ethene - NA	NA	Within 80 days of injection PCE, TCE, and DCE concentrations had been reduced by approximately 64%, 10%, and 56% respectively in one monitoring well installed an unknown distance downgradient from the emplacement area.
Japanese Electrical Plant	Japan	Electrical plant	NA	NA	NA	HRC accelerated the natural attenuation process.
Coopervision Manufacturing Facility	Scottsville, NY	NA	NA	NA	NA	NA
Invensys Control	Old Saybrook, CT	Electronics Manufacturing Plant	PCE - 13.9	PCE - 0.01	NA	Within 9 months after the pilot scale injection PCE concentrations had decreased by 99% in one well installed an unknown distance from the injection area. No other data has been provided for this site.
Manufacturing Facility	Brighton, NY	Manufacturing facility	NA	NA	NA	NA
Arlington Cleaners	Arlington, TX	Drycleaning Facility	PCE - 4.5 TCE - 1.0 DCE - 7.3 VC - 0.87 Ethene - NA	PCE - 0.41 TCE - 0.09 DCE - 0.44 VC - 0.13 Ethene - NA	NA	Within 18 months after the pilot scale injection PCE, TCE, DCE, and VC concentrations had decreased by 98%, 91%, 94%, and 85% respectively at one well installed within or downgradient from the injection area. No ethane concentration data was provided for this site.
Edible Oils						
Former Zipper Manufacturing Facility	Newport News, VA	Manufacturing facility	PCE - 120.0 TCE - 8.0 DCE - 14.0 VC - 1.3 Ethene - 0.623	PCE - 34.0 TCE - 11.0 DCE - 27.0 VC - 5.3 Ethene - 0.87	1,2-DCA	NA

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Edible Oils (Continued)						
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	Aircraft maintenance and cleaning	PCE - 1.8 TCE - 260 DCE - 78 VC - 0.95 Ethene - 0.62	PCE - 0.048 TCE - 310 DCE - 190 VC - 13 Ethene - 0.05	None	None
Site N-6, Former NSA Mid-South	Millington, TN	Aircraft maintenance and cleaning	TCE - 1.8 DCE - 0.034 VC - ND Ethene - 0.005	TCE - 1.2 DCE - 0.25 VC - ND Ethene - 0.0003	CT: 0.26 mg/L	None
Site SS-015, Travis AFB	Travis AFB, CA	Aircraft maintenance and cleaning	PCE - 1.0 TCE - 4.2 DCE - 13 VC - 17	PCE - 0.43 TCE - 2.2 DCE - 4.0 VC - 0.55	Benzene: 0.012 mg/L Chlorobenzene: 0.50 mg/L	None
Site FF-87, Former Newark AFB	Newark, OH	Former hazardous waste storage area	PCE - 0.34 TCE - 0.013 DCE - 0.046 VC - ND Ethene - 0.00048	PCE - 0.74 TCE - 0.008 DCE - 0.036 VC - 0.020 Ethene - N/A	None	None
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	Manufacturing facility	TCE - 6.7 DCE - 0.22 VC - ND Ethene - ND	TCE - 6.2 DCE - 1.8 VC - 0.002 Ethene - 0.25	None	At approximately 5 months after injection TCE concentrations were approximately the same as baseline conditions. However, cis-1,2-DCE and ethene concentrations detected at 5 months post injection were substantially higher than the baseline event.
Former Radiator Facility	IL	Manufacturing facility	TCE - 1.3 DCE - 7.4 VC - 0.22 Ethene - N/A	TCE - <1 DCE - 41 VC - 8.3 Ethene - N/A	NA	None
Site SS-17	Altus AFB, OK	Industrial area	TCE - 1.66 DCE - 0.90 VC - 0.44 Ethene - 0.007	TCE - 0.65 DCE - 1.07 VC - 0.79 Ethene - 0.11	NA	Within approximately 5 months the TCE maximum concentration had been reduced by approximately 61%. DCE, VC, and ethene maximum concentrations increased by approximately 19%, 80%, and 1,470% respectively. TCE concentration reductions were observed in all of the injection wells and monitoring wells with per well reductions ranging from 13 to 99%.

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
OU-1 Landfill 3	Altus AFB, OK	Landfill	TCE - 10.4 DCE - 0.5 VC - < 0.12 Ethene - < 0.03	TCE - 6.55 DCE - 0.8 VC - 0.24 Ethene - 0.79	NA	Within approximately 5 months the TCE maximum concentration had been reduced by approximately 37%. DCE, VC, and ethene maximum concentrations increased by approximately 60%, 80% and an order of magnitude, respectively. TCE concentration reductions were observed in all wells except injection well 6, with per well reductions ranging from 23 to 92%.
Whiteman Air Force Base LF-08	Whiteman AFB, MO	Landfill leachate plume	TCE - 2.1 DCE - 0.033 VC - ND Ethene - <0.001	NA	None	The first process monitoring round is scheduled for October 2002.
SOLID SUBSTRATES						
Bark Mulch						
Building 301, Offutt AFB	Omaha, NE	Aircraft Manufacturing and Maintenance	TCE - 1.9 DCE - 0.27 VC - 0.0023 Ethene - ND	TCE - 1.22 DCE - 0.098 VC - 0.004 Ethene - 0.008	None	61 percent reduction in mean TCE concentration downgradient of biowall
OU1 Landfill 3	Altus AFB, OK	Landfill Leachate	Upgradient Well TCE - 6.2 DCE - 0.85 VC - ND	Biowall Well MP-01 TCE - 0.048 DCE - 0.64 VC - ND	None	Concentration data after 4 weeks of installation. Limited evidence of degradation of TCE to DCE.
Naval Weapons Industrial Reserve Plant	McGregor, Texas	Release of Ammonium Perchlorate as Rocket Fuel Component	Perchlorate - 27 (Pilot-Test)	Perchlorate - ND	TCE	Full-scale System Installed
Chitin						
Distler Brickyard Superfund Site	Louisville, KY	Brick production	TCE - 0.007 (est.) DCE - 0.09 (est.) VC - 0.016 (est.) Ethene - 0.027 (est.)	TCE - ND (est.) DCE - 0.058 (est.) VC - 0.009 (est.) Ethene - 0.011 (est.)	None	Intermittent wetting of contaminant zone by infiltration
HYDROGEN						
Gaseous Hydrogen Injection						
Launch Complex 15	Cape Canaveral, FL	Former rocket launching facility	TCE - 87 DCE - 370 VC - 52 Ethene - 7.3	TCE - 66 DCE - 270 VC - 67 Ethene - 11	None	50 (at 15 feet from injection point) to 90 (at 3 to 6 feet from injection point) percent reduction in total chlorinated ethenes in treatment zone over 18 months.
Offutt AFB	Omaha, NE	NA	TCE - N/A DCE - 0.43 VC - N/A Ethene - N/A	TCE - N/A DCE - <0.005 VC - N/A Ethene - N/A	NA	Small scale pilot test, complete cis-1,2-DCE (over 99%) removal.

TABLE 4.3 SUMMARY OF GROUNDWATER CONTAMINANT DATA (Continued)

Site Name (Sorted by Substrate)	Site Location	Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Gaseous Hydrogen Injection (Continued)						
Twin Cities Army Ammunition Plant	New Brighton, MN	Former Army Munitions Plant	NA	NA	NA	A decline in concentrations of TCE and DCE was observed, with an increase in VC and ethene after a lag period

[a/] NA indicates the data are not available.

TABLE 4.4 SUMMARY OF GROUNDWATER GEOCHEMICAL DATA

Site Name	Site Location	Total Organic Carbon		Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Metl
		Maximum Pre-Treatment (mg/L)	Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)
Lactate																
Bachman Road Residential Well Site	Oscoda, MI	NAa/	NA	0.5 to 2	< 0.5	Approximately 200	Approximately +100	7.1 to 7.6	7.1 to 7.6	NA	NA	NA	NA	NA	NA	NA
Area 6, Dover AFB	Dover AFB, DE	NA	18	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Former Drycleaning Facility	WI	NA	NA	4.2 - 6	0.33 - 2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Test Area North (TAN), INEEL	ID	NA	NA	0.1 - 2.6	0 - 0.3	+44 to +310	-230 to +260	NA	NA	0.9 - 2.6	0.1 - 2.3	NA	NA	34 - 41	3 - 41	NA
Ogallala Superfund Site	Ogallala, NE	2.4	210	NA	NA	NA	NA	NA	NA	11	6	NA	NA	134	< 10	NA
NAS Fallon	Fallon, NV	NA	NA	NA	NA	-250	-400 to -250	7.6 to 9.1	NA	< 0.09	NA	NA	NA	809 to 8,890	NA	NA
Former PEC Industries Site	Orlando, FL	18 - 46	NA	< 1.1	NA	-190 to +120	NA	5.1 to 6.0	NA	< 0.02 - 0.08	NA	0.5 to 13.7	NA	0 to 78	NA	3.1 to 3,325
Cape Canaveral Facility 1381	Cape Canaveral, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Watertown Industrial Area	Watertown, MA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.2 - 0.3
Aerojet Superfund Site	CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Naval Air Station Point Mugu IRP Site 24	CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.7	0.005	< 1
Weyerhauser Sycan Maintenance Shop	Beatty, OR	NA	NA	NA	NA	+25	-400 - -520	6.9	5.4	NA	NA	NA	NA	NA	NA	NA
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Southern US Industrial Site	Unknown	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Molasses																
Avco Lycoming Superfund Site	Williamsport, PA	2	40	0.8 to 5	NA	45 to +239	-120 to +116	NA	5.9 to 6.8	NA	NA	NA	<1 to 20	NA	<2.5 to 170	NA
Cedarburgh Drycleaners	Cedarburgh, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Industrial Site	Central Ohio	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Washington Square Mall	Germantown, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	Greenville, SC	6.3	NA	0.95 - 3.22	NA	64 - 246	-50 average	3.8 - 5.6	NA	ND - 0.1	NA	ND - 1.8	NA	ND - 12.5 (av. 3.1)	NA	NA
Crestwood Site	Glendale, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Emeryville Manufacturing Facility	Emeryville, CA	NM	NM	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	Northeastern USA	2	469 (MW) >3000 (inj)	NA	NA	NA	NA	7	3.7	NA	NA	NA	NA	NA	NA	NA
Nuclear Fuel Services Site	Erwin, TN	5	31	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
TRW Automotive	Rogersville, TN	2	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hanscom AFB	Bedford, MA	6.2	525	0.35 - 1.48	0 - 0.7	-57.5 to +200	-167 to -44	5.7 - 7.1	5.9 to 7.1	ND	ND - 0.27	0.15 - 12.3	ND to 142	21.5 - 38.9	0.22 - 30.1	15 - 139
Vandenberg AFB	Lompoc, CA	4.8	4260	1.68 - 4.8	0 - 2.5	+337 to +439	-301 to +188	6.2 - 6.7	4.1 - 6.1	4.7 - 11.3	ND - 11.7	ND - 0.038	ND - 135	183 - 306	6.5 - 418	ND - 6
Ohio Industrial Site	Southwestern Ohio	NA	NA	NA	NA	NA	NA	6.9	5.5	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	Southeast England	14.5	11	3.68 - 4.8	0.02 - 0.32	+37 - +39	-113 - -178	6.63 - 6.81	6.95 - 7.1	0.6 - 0.7	<0.3 - 0.9	<0.1 - 9.0	5.33	160 - 210	33 - 124	0.078 - 0.143
Former Manufacturing Facility	North Carolina	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Butyrate																
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	120	NA	< 1	NA	NA	Approximately -200	7.0 to 7.8	NA	NA	NA	NA	NA	NA	NA	NA
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Methanol/Acetate																
Building 360, Kelly Air Force Base	South Central TX	NA	NA	Approx. 2	NA	Aerobic conditions with small anaerobic pockets and zones	NA	NA	NA	Approx. 24	NA	Approx. 0.06	NA	Approx. 16	NA	ND
Rademarkt Site	Groningen, Netherlands	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

TABLE 4.4 SUMMARY OF GROUNDWATER GEOCHEMICAL DATA (Continued)

Site Name	Site Location	Total Organic Carbon		Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane	
		Maximum Pre-Treatment (mg/L)	Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)
Lactose																	
Former Municipal Waste Water Treatment Facility (Lactose)	NH	0 - 10 mg/L (COD)	~ 10,000 mg/L (COD)	0.2 to 7.4	0 - 1.8	-55 to +310	-290 to +10	6.5-7.8	6.5-7.8	< 3.6	<0.05	NA	NA	20-35	<10	< 5	< 10
Fructose																	
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sodiom Benzoate																	
New England Super Fund Site	New England	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ethanol																	
Sages Drycleaner	Jacksonville, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SEMI- OR SLOWLY-SOLUBLE SUBSTRATES																	
HRC™																	
Contemporary Cleaners	Orlando, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Decorah Shopping Center Drycleaners	Decorah, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dixie Cleaners	Jacksonville, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dover Park Plaza Drycleaning Facility	Yardville, NJ	1	720	2.4 - 5.3	0.3 - 0.7	+106 to +287	-146 to +37	4.5 - 6.1	4.1 - 6.5	NA	NA	ND - 5.0	3.8 - 5.6	36 - 67	2 - 67	< 0.007	< 1.44
Former Industrial Filter Manufacturer	Rochester, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Former Landfill Site 7, Duluth International Airport	Duluth, MN	ND	300	NA	NA	88	-40	NA	NA	NA	NA	Approx. 2	Approx. 40	NA	NA	ND	Approx. 1
Watertown Industrial Area	Watertown, MA	NA	1.2 - 5 feet from injection well	NA	0 - 1	NA	-190 to +200	NA	5.8 - 6.8	NA	NA	NA	NA	NA	NA	NA	NA
Former Manufacturing Site	Walled Lake, MI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Unocal Wichita	Wichita, KS	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
FMC Corporation Site	San Jose, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.07 - 23.33	0.28 - 3.87	93 - 270	98 - 270	6 - 106	79 - 524
Hayden Island Cleaners	Portland, OR	NA	NA	NA	NA	< 100	NA	NA	NA	2.1 - 2.3	0.25 - 1.2	0.315	0.02 - 8.74	37364	7.7 - 25	NA	0.0005 - 0.612
Naval Air Station Dallas	Dallas, TX	6.7	12.8	0.3	0.05	102.1	50	6.68	6.62	0.2 N	1.2 N	< 0.03	0.049	1586	2410	< 0.01	0.318
Naval Air Warfare Center	Indianapolis, IN	1.2	95.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hurlburt Field	Tallahasse, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Industrial Site	NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Closed Industrial Facility	CO	NA	NA	0.75 to 2.68	NA	-25 to +269	-429 to +335	NA	NA	< 0.1 to 0.4	NA	NA	NA	57 to 75	< 10	NA	NA
Site 1, Santa Clara County	Santa Clara County, CA	5	240	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site 2, Santa Clara County	Santa Clara County, CA	4.1	1600	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tosco Manufacturing Facility	Burien, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Strip Mall Dry Cleaner	Kent, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dayco Manufacturing Facility	Eldora, IA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	25.9	21.4	NA	NA
Moen Manufacturing Facility	Elyria, OH	9	880 - 30 days after injection 310 - 180 days after injection	NA	NA	NA	NA	6.45	5.62	NA	NA	24	53	310	62	NA	NA
Springdale Drycleaners	Portland, OR	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Reichhold Chemicals	Tacoma, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Acton Mickelson Ordinance Facility	Hollister, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	NA	NA	5.05	NA	+138	NA	7.41	NA	6.1	NA	0.04	NA	229	NA	NA	NA
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	Crozet, VA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Flemington Manufacturing Facility	Flemington, NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	35.9	24.5	54.5	36.8	NA	NA
Japanese Electrical Plant	Japan	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
HRC™ (Continued)																	

TABLE 4.4 SUMMARY OF GROUNDWATER GEOCHEMICAL DATA (Continued)

Site Name	Site Location	Total Organic Carbon		Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane	
		Maximum Pre-Treatment (mg/L)	Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)
Coopervision Manufacturing Facility	Scottsville, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Invensys Control	Old Saybrook, CT	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	Brighton, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Arlington Cleaners	Arlington, TX	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Edible Oils																	
Former Zipper Manufacturing Facility	Newport News, VA	910	560	< 1	< 1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.6 - 9.2	0.92 - 5.4
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	54.9	6.2	<0.1 to 0.23	0.09 to 0.20	-35 to -154	-126 to -191	7.03 to 7.84	7.04 to 7.23	<0.05 to 0.10	0.02J	1.96 to 2.05	3.19 to 4.0	19.2 to 29.9	2.9 to 32	0.09 to 0.96	0.22 to 0.25
Site N-6, Former NSA Mid-South	Millington, TN	<5.0	2400	0.2 to 1.4	0.4 to 6.1	+253 to -359	+66 to -130	6.26 to 6.99	5.30 to 6.82	0.051 to 1.7	0.050J to 1.7	0.23 to 3.5	<0.01 to 16.5	<1 to 19	<1	8.6 to 108	25 to 13,000
Site SS-015, Travis AFB	Travis AFB, CA	6.1	620	0.42 to 6.58	0.42 to 4.23	+52 to +264	-63 to -336	6.23 to 6.94	6.00 to 7.06	<0.05 to 0.27	<0.1	0.2 to 2.2	<0.01 to 11	Unknown	170 to 3100	9.9 to 113	4.5 to 3,500
Site FF-87, Former Newark AFB	Newark, OH	23	500	0.20 to 1.78	NA	-74 to -238	NA	6.43 to 7.33	NA	0.04 to 0.08	0.01 to 0.05	0.09 to 3.49	Unknown	59 to 129	2 to 110	0.98 to 14	NA
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	2.4	26000	0.22 to 2.28	< 0.01 to 1.77	+74 to -158	-136 to -395	6.8 to 7.12	5.10 to 7.09	< 0.01	< 0.1 to 2.85	< 0.01 to 0.70	< 0.01 to 3.9	100 to 230	7 to 220	ND	ND
Former Radiator Facility	IL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site SS-17	Altus AFB, OK	7.7	7300	0.17 - 4.53	0.5 - 1.6	+70 - -173	-76 - -230	7.0 - 7.8	4.9 - 7.1	<0.5 - 0.3	< 0.5	0.01 - 1.16	NA	107 - 2,011	2.5 - 1,400	0.008 - 1.82	0.054 - 19.0
OU-1 Landfill 3	Altus AFB, OK	23	11000	0.16 - 3.8	< 0.1 - 0.6	+49 - +81	-51 - +138	7.0 - 7.2	4.7 - 7.0	2 - 6.1	<0.5	0.07 - 0.3	25 - 50	1,559 - 2,112	100 - 2,175	<16	16 - 890
Whiteman Air Force Base LF-08	Whiteman AFB, MO	< 5.0	NA	1.8 to 8.9	NA	-53 to +146	NA	6.96 to 7.92	NA	17 to 23	NA	< 0.007 to 0.34	NA	83 to 120	NA	0.001 to 0.002	NA
SOLID SUBSTRATES																	
Bark Mulch																	
Building 301, Offutt AFB	Omaha, NE	24	Mean: 1.3	1.0 to 2.5	Mean: 0.03	133.2 to 182.6	Mean: 169.5	6.88 to 7.91	Mean: 6.44	<0.05 to 6.4	Mean: 16.75	<0.02 to 0.06	Mean: <0.2	35.0 to 74.6	Mean: 16.75	<0.0012 to 0.099	NA
OU1 Landfill 3	Altus AFB, OK	<10 (background)	2,800 (biowall)	<0.1 to 4.5 (background)	<0.1 (biowall)	20 to 107 (background)	-266 to -365 (biowall)	6.8 to 7.2 (background)	6.43 to 6.75 (biowall)	<0.1 to 9.5 (background)	<0.5 (biowall)	<0.1 (background)	3 to 4	1,600 to 2,200 (background)	410 (biowall)	<1 (background)	7.9 to 8.8 (biowall)
Naval Weapons Industrial Reserve Plant	McGregor, Texas	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Chitin																	
Distler Brickyard Superfund Site	Louisville, KY	NA	NA	NA	NA	NA	NA	NA	NA	0.3	0.35	2	3	30	1	0.2	425
HYDROGEN																	
Gaseous Hydrogen Injection																	
Launch Complex 15	Cape Canaveral, FL	NA	NA	8.0 median	NA	NA	NA	NA	NA	5.8 median	NA	NA	NA	NA	NA	0.027 - 3.7	0.033 - 3.1
Offutt AFB	Omaha, NE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Twin Cities Army Ammunition Plant	New Brighton, MN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

[a/] NA indicates the data are not available.

TABLE 4.5 SUMMARY OF BIOREMEDIATION SYSTEM DESIGN

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Depth (feet)					
Lactate													
Bachman Road Residential Well Site	Oscoda, MI	Pilot	Lactate	NAa/	NA	Bioaugmentation, nitrogen, phosphorous	270	8	Two injection wells; one extraction well; network of monitoring points around the plot. Lactate was injected as a 6% solution in water.	September 2000; 140 days injection	Ongoing	NA	NA
Area 6, Dover AFB	Dover AFB, DE	Pilot	Sodium lactate	NA	NA	Bioaugmentation with a microbial culture from the DOE Pinellas Site, ammonia, and phosphate	2400	5	3 injection wells, screen 38-48' bgs. Closed loop recirculation cell w/ 3 recovery wells. Cyclic injection of nutrients and unamended GW.	April 1998 to June 1999 - Pilot	Implemented Bioaugmentation, Pilot Test Complete	NA	NA
Former Drycleaning Facility	WI	Full	Lactate; 200 mg/L	NA	NA	Amended with 2 mg/L yeast extract, sodium sulfite	NA	NA	Injection wells. The four injections after the first were made under pressure to reduce biofouling.	August '97 - April 2000	Performance monitoring	About every 6 weeks	NA
Test Area North (TAN), INEEL	ID	Pilot	9600 gallons of Sodium lactate	$ 0.70 to $0.80	Approximately $54,000	Sodium bromide	700	200	300 gallons of sodium Lactate was injected weekly for 8 months.	November 1998 - current	Ongoing	Biweekly for the first 9 months, sampling frequency unknown after the 9 month point	NA
Ogallala Superfund Site	Ogallala, NE	Pilot	Sodium lactate injected at about 60% lactate in water in 3 to 4 week intervals over 10 months.	NA	NA	Potassium Bromide	Approximately 420	10	One extraction well, two injection wells, 6 monitoring wells installed. Substrate injection was performed concurrently with groundwater extraction from the downgradient extraction well to form a closed recirculation system.	April 1999 to current	Site groundwater monitoring continues to date.	Monthly for the first year, approximately annually thereafter.	NA
NAS Fallon	Fallon, NV	Pilot	Lactate	NA	NA	Yeast extract, vitamins	NA	NA	Recirculation with nutrient addition	500 days	NA	NA	NA
Former PEC Industries Site	Orlando, FL	Pilot	Sodium Lactate	NA	NA	Ammonia and ortho-phosphate	Approximately 12,000	10	Each treatment cell consists of 4-5 extraction wells on cell perimeter around central injection well.	2001 (planned)	The injection phase of this pilot test was planned for 2001, monitoring was to have been conducted through 2002.	NA	The well installation and baseline monitoring phases have been completed as of May 2001. The injection phase was scheduled for 2001 while monitoring was to be extended through 2002.
Cape Canaveral Facility 1381	Cape Canaveral, FL	NA	Lactic Acid; 7.6 L/min at 3mM	NA	NA	None	340	10	Two communicating (recirculation) wells, 13 tri-level groundwater monitoring probes, and upgradient and downgradient monitoring wells.	149 days	Demonstration Complete	Biweekly	Rapid dechlorination of TCE and cDCE to VC, followed by slower subsequent dechlorination of VC to ethene under sulfate and methanogenic conditions
Watertown Industrial Area	Watertown, MA	Pilot	Lactic acid	NA	NA	Amended with ammonia chloride, tripolyphosphate, yeast extract, and sodium hydroxide	NA	NA	System of injection and recirculation cells	NA	NA	NA	After 8 months of anaerobic operation, the system was converted to an aerobic circulating cell for 3 months.- ORC,methane addition => 70% reduction of total ethenes in 11 months.
Aerojet Superfund Site	CA	Pilot	Lactic acid	NA	NA	Bioaugmentation with a commercially produced microbial augment (KB-1)	NA	NA	NA	September 2000/NA	NA	NA	NA
Naval Air Station Point Mugu IRP Site 24	CA	Pilot	1020 gallons of lactic acid as a 88% in water mixture	NA	NA	None	5000	10	One extraction well, one injection well and 5 monitoring wells. Groundwater was circulated in a closed loop between the extraction well and the injection well.	December 1998, 1 year	Pilot Test Complete/ follow up unknown	Biweekly for the first 12 months.	NA
Weyerhauser Sycan Maintenance Shop	Beatty, OR	Pilot	Lactic Acid	NA	NA	Potassium Bromide, TCFE	80	10	Injection and monitoring system was placed to inject into and monitor changes within the upper aquitard. One well was used for groundwater extraction, substrate injection, and process monitoring.	NA	Pilot test complete/ follow up unknown	Monthly for the first 3 months.	NA
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	Pilot	Lactic Acid	NA	NA	Vitamin B12, yeast extract	NA	NA	NA	NA	Pilot test complete/ follow up unknown	2 process monitoring events 6-7 weeks apart.	NA

TABLE 4.5 SUMMARY OF BIOREMEDIATION SYSTEM DESIGN (Continued)

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Depth (feet)					
Lactate (Continued)													
Southern US Industrial Site	Unknown	Full	Lactate and Acetate	NA	NA	Ammonium Phosphate	150000	25	36 dual extraction wells run on average approximately 60% of the time. Substrate is injected periodically through 7 injection wells.	March, 1998/ ongoing	Monitoring continues to date	Biannually through September 1999	NA
Molasses													
Avco Lycoming Superfund Site	Williamsport, PA	Pilot, Full	Molasses	NA	NA	None	Approximately 5,000	11	20 injection wells - flow rate controlled by PLC	November 1995 to June 1996 - Pilot January 1997 to July 1998 - Full	Ongoing	Quarterly	NA
Cedarburgh Drycleaners	Cedarburgh, WI	Full	Molasses	NA	NA	None	11550	25 - 28'	Geoprobe, infiltration gallery	NA	NA	Semiannual	NA
Industrial Site	Central Ohio	Pilot	Molasses	NA	NA	Sodium Phosphate, ammonium Chloride, monopotassium phosphate	Phase 1: 500 Phase II: 4,500 Phase III: 32,000	25	Phase I consisted of 1 injection well, 1 injection well, and 1 monitoring well. Phase II consisted of 2 injection wells and 9 monitoring wells. Phase III used the same injection wells installed for Phase II but added 20 more monitoring wells.	November 1996 / 5 years	NA / NA	Monthly for 6 months	Phase I was designed to confirm the capability of enhancing reductive dechlorination in-situ. Phase II was designed to evaluate amendment distribution strategies. Phase II was designed to the maximum volume of aquifer that could be impacted by a single well injection. Contaminant concentration data were collected during Phase I only.
Washington Square Mall	Germantown, WI	Full	Molasses (47% carbohydrate during pilot; 66% during full)	NA	NA	None	30000	5	Geoprobe, infiltration gallery	August '98; 6 months - Pilot March '99; 6 months - Full	Site closed	Quarterly	Site closure from WDNR, less than 2.5 yrs after initiating the in situ reaction zone
Manufacturing Facility	Greenville, SC	Full Scale	Molasses	$1.25/gal.	$30,000/yr.	None	170000	25 - 73	Fully automated	2 years		Monthly for TOC Quarterly for VOCs	NA
Crestwood Site	Glendale, WI	Full	Molasses	NA	NA	NA	NA	NA	Geoprobe, infiltration gallery	NA	NA	NA	NA
Emeryville Manufacturing Facility	Emeryville, CA	Pilot, Full	Molasses	$3.00 per gallon	NA	Anaerobic digester sludge	NA	NA	91 injection pts with Geoprobe	NA	NA	NA	Closure, all contaminant concentrations were below MCLs.
Manufacturing Facility	Northeastern USA	Full	Molasses, 200 gal; 10% carbohydrates in each well	0.3	$5,000/year	none (Zero valent iron proposed for source area 2002.)	450000	50-190	Batch delivery under pressure to 11 injection wells	2 to 5 years of injections	Ongoing	Quarterly	Full-scale containment in place in mid-plume 2000 to 2002. Full scale source area injection program began in October 2001.
Nuclear Fuel Services Site	Erwin, TN	Pilot	Molasses; 363 gallons	0.15	NA	None	NA	NA	NA	8 months	NA	NA	The pilot scale application was considered a success and full scale applications are scheduled for "designated source areas" in the 2nd quarter of 2002.
TRW Automotive	Rogersville, TN	Pilot	Molasses; 220 gallons	0.15	NA	None	NA	NA	NA	4 months	NA	NA	Closure monitoring ongoing.
Hanscom AFB	Bedford, MA	Pilot	Molasses: roughly 20 gallons every two weeks	NA	NA	None	~5000	50	One injection well. Manual, pressurized injections. Post-injection water pushes.	June 2000; ongoing	Ongoing	About monthly for process parameters. About quarterly for COCs, dissolved gasses, etc.	AFCEE/ESTCP Demonstration.
Vandenberg AFB	Lompoc, CA	Pilot	Molasses: variable frequency and amount based on injection well process monitoring data.	NA	NA	None	~1000	30	Three injection wells. Manual, pressurized injections.	April 2001; ongoing	Ongoing	About monthly for process parameters. About quarterly for COCs, dissolved. gasses, etc.	AFCEE/ESTCP Demonstration.
Ohio Industrial Site	Southwestern Ohio	Full	5 to 10 percent molasses solution biweekly for 6 months, intermittent thereafter	NA	NA	None	NA	NA	Reactive barrier configuration	Ongoing for over two years	Ongoing	Every 3-4 months on average	NA

TABLE 4.5 SUMMARY OF BIOREMEDIATION SYSTEM DESIGN (Continued)

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Depth (feet)					
Molasses (Continued)													
Manufacturing Facility	Southeast England	Full	Molasses, 35,805 lb through September 2002	0.2	7161	None	NA	NA	A total of 53 injection wells wer installed under the future site of a new building. Each injection well was piped separately to the injection system installed in a separate building so that substrate injection could be controlled by well. 7 monitoring wells were installed up and down gradient from the injection area. During the first two years 15,000 lb were injected at a rate of 21 lb/day. In 9/01 the feed rate was increased to 57 lb/day. Injection was ongoing at the increased rate through spring 2002.	June 1999 / NA	Substrate injection and process monitoring are ongoing	Quarterly	During the life cycle of this application substrate injection rates have been very carefully monitored and controlled in order to control the rate of reductive dechlorination. The rate of reductive dechlorination had to be strictly controlled so that DCE and VC did not accumulate and intrude in to the building constructed above the injection area.
Former Manufacturing Facility	North Carolina	Pilot	NA	NA	NA	NA	NA	NA	NA	NA / 1 year	Ongoing	quarterly	PCE and TCE concentration decreases of 89% and 94% respectively, were reported although analytical data was not provided.
Butyrate													
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	Microcosms, Pilot	Butyric acid (3mM) at 236 gal/day (0.62 L/min)	NA	NA	Yeast extract, 20 mg/L	45	3	Single injection well, single extraction well, and nine monitoring points at depths of 24 to 27 feet bgs	194 days	Demonstration Complete	Biweekly	On average, 87% of injected chloroethenes could be accounted for, with ethene levels accounting for approximately 50% of the total chloroethene concentration.
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	Microcosms, Pilot	Butyric acid; 1.5 L/min	NA	NA	Yeast extract, 20 mg/L; Sodium bicarbonate, 279 mg/L	120	3	Three injection wells spaced 2 ft apart; system of monitoring wells; existing well in zone of contamination used to supply injection water for test plot	179 days	Demonstration Complete	Biweekly	Calculated TCE half lives of 4.4 to 4.7 hours. cDCE accumulated with VC comprising a small percentage of overall mass. Ethene and ethane remained at or below detection.
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	Microcosms, Pilot	Butyric acid; 0.65 L/min	NA	NA	Yeast extract, 20 mg/L	120	3	Three injection wells, nine monitoring wells at depths of 45 to 48 feet bgs.	180 days	Demonstration Complete	Biweekly	NA
Acetate													
Hanford 200 Area Site	Richland, WA	Pilot	Acetate	NA	NA	Nitrate	400	10	One injection well and one extraction well were installed and run continuously as a recirculation system two monitoring wells were installed between the injection and extraction wells for process monitoring.	January 1995/ 14 months	Pilot Test Complete	NA	Acetate and nitrate were injected and recirculated through 2 aquifer zones to treat carbon tetrachloride and nitrate contamination. Approxiamtely 30 kg (dry weight) of bacterial biomass was produced and approximately 2 kg of CT was broken down during the course of the 14 month pilot study.
Gillette Company Site	Eastern US	NA	Acetate	NA	NA	Methanol and microbial amendment KB-1	NA	NA	One injection well and one extraction well were installed. Acetate was injected to reduce sulfate mass and to push geochemistry to more reducing conditions. 3 months after acetate injection, bioaugmentation with methanol and KB-1 was performed.	NA/NA	NA/NA	NA	This site had high sulfate (>1000 mg/L), high salinity, and tidal impact due to close proximity of the coast. The target zone was also deep >100 ft. TCE degradation to DCE was noted early on but DCE degradation and VC/ethene accumulation was not observed until 4 months after bioaugmentation with the KB-1 commercial bioaugmentation product.

TABLE 4.5 SUMMARY OF BIOREMEDIATION SYSTEM DESIGN (Continued)

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Depth (feet)					
Acetate (Continued)													
Manufacturing Facility	NJ	Pilot	Acetate, 1000 lb	NA	NA	NA	NA	NA	NA	NA	NA/NA	NA	Acetate injection into a surficial overburden aquifer/fractured bedrock aquifer.
Methanol/Acetate													
Building 360, Kelly Air Force Base	South Central TX	Bench and Pilot	Methanol and Acetate	NA	NA	Bromide, KB-1 ("A naturally occurring microbial consortia isolated by GeoSyntec and Univ. of Toronto")	90	25	Closed loop circulation system consisting of 3 extraction wells, 1 injection well and 5 monitoring wells	December, 1999 / 320 days	Pilot Test Complete	Variable	DCE degradation was not observed until after the KB-1 microbial consortium was added.
Rademarkt Site	Groningen, Netherlands	Pilot	0.35% methanol, 1.44% compost leachate, 0.9 g/L ammonium chloride	NA	NA	ammonium chloride, sodium bromide	5000	10	10 Injection wells were installed upgradient of 5 extraction wells. Groundwater was extracted, amended, and reinjected.	NA / 35 weeks	Pilot test was completed	NA	This application used methanol and compost leachate as a substrate to augment reductive dechlorination already occuring at the site.
Lactose													
Former Municipal Waste Water Treatment Facility (Lactose)	NH	Full	Lactose (approx. 70%) and Yeast Extract (approx. 30%) (proprietary blend)	0.22	27775	Proprietary mixture of lactose and yeast extract	~3.5 acres	150 feet bgs	Injection of blend pumped into 3 locations: 5,050 lbs biostimulant per 65,950 gallons injected during pilot; 22,100 lbs per 375 gallons injected during full-scale	1997-2000 - pilot 2000-2003 - full-scale 2003-pursue closure with MNA	Full scale in progress (scheduled until 2003)	Tri-annual	Monitoring program specified contaminants of concern DO, ORP, and COD. If COD concentrations exceed 25mg/L, then no other indicator parameters (e.g., nitrate, sulfate, methane, etc.) were deemed required.
Fructose													
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	Pilot	Fructose	NA	NA	Acetate	NA	NA	Recirculation system with one downgradient extraction well.	March 2000	Pilot test complete with continued monitoring, Currently preparing CMS	NA	NA
Sodium Benzoate													
New England Super Fund Site	New England	Pilot	Sodium Benzoate, injected as a 4 mg/L solution at a rate of 5 liters per point per day. As of December 1999 2,147 lb of substrate had been injected.	NA	NA	NA	NA	NA	30 electron donor injection points installed in sets of three (three injection intervals) in a barrier configuration. I upgradient and 3 downgradient rows of monitoring wells are used for process monitoring.	January 1998, 2 years	NA	biweekly for 1998, monthly for 1999	NA
Ethanol													
Sages Drycleaner	Jacksonville, FL	Pilot	Ethanol 8,980 gallons injected as a 95% ethanol in water mixture.	NA	NA	methanol, n-hexanol, and 2-ethyl-1-hexanol as tracers	130	10	3 injection wells surrounded by 6 recovery wells. Ethanol was injected at a total of 15 liters per minute for three days. Groundwater was extracted at a rate of 30.4 liters per minute to ensure containment of injected fluids.	June 1998 / 1 year	NA / NA	NA	The PCE extraction efficiency for the ethanol flush was approximately 63%. Approximately 718 gallons (8% of the total volume) of ethanol and an unknown quantity of methanol (10% of the injected volume) were left in the subsurface after flush activities were complete. Process monitoring results were not provided.

TABLE 4.5 SUMMARY OF BIOREMEDIATION SYSTEM DESIGN (Continued)

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Depth (feet)					
SEMI- OR SLOWLY-SOLUBLE SUBSTRATES													
HRC™													
Contemporary Cleaners	Orlando, FL	Full	HRC; 6,800-lbs was injected into the shallow aquifer 18 months later 6,810 pounds were injected into the deep aquifer	6	$40,800 1st application $40,860 2nd application	None	14600	15	144 injection points installed within the upper aquifer on a 10 foot grid spacing. Second injection consisted of 145 injection points on a 10 foot grid.	NA/1 year	NA	Monthly for the first 6 months	Two HRC applications were performed on this site. The first application was performed in the shallow aquifer. The second application was performed 18 months later in the deep aquifer because the first application did not appear to be affecting contaminant mass present in the deep aquifer.
Decorah Shopping Center Drycleaners	Decorah, WI	Full	HRC; 3,000 lbs (forecast)	NA	NA	None	7875	NA	20 injection points	NA	NA	NA	NA
Dixie Cleaners	Jacksonville, FL	Pilot	HRC; total of 22,000 pounds	NA	150000	None	18400	10	175 injection points installed on a 10 foot grid spacing. 30 monitoring wells, 10 installed within each aquifer zone.	June 2000; 1 year	Considering methanotrophic insitu system	Bimonthly for the first year, quarterly thereafter.	Groundwater results from pilot test showed a sharp decrease in the concentrations of PCE and TCE
Dover Park Plaza Drycleaning Facility	Yardville, NJ	Pilot and Full	Pilot - 210 lb HRC Full - 4,860 lb HRC	Pilot - $7.86 Full - $6.00	Pilot - $1,650 Full - $29,160	None	Pilot - 42 Full - 3,900	5	Pilot - 8 direct injection wells installed in a semicircle 2.5 feet from one monitoring well. A second monitoring well was installed 3 feet downgradient from the outside edge of the injection point circle. Full - 159 injection points installed in 3 grids and 1 barrier.	NA	NA	Pilot - 16, 48, and 72 days following injection Full - Monthly for the first 6 months, quarterly thereafter.	NA
Former Industrial Filter Manufacturer	Rochester, NY	Full	HRC; 35 lbs/hole	NA	NA	None	900	15	21 injection points at 5-ft centers using a Geoprobe rig	NA	Site Closed	Quarterly for the first 15 months	Site closure recommneded based on monitoring results
Former Landfill Site 7, Duluth International Airport	Duluth, MN	Pilot	HRC; 180 lbs	NA	NA	None	NA	NA	9 injection points using a Geoprobe rig	April 2000	NA	~ Every 7 weeks	NA
Watertown Industrial Area	Watertown, MA	Pilot	HRC	NA	NA	NA	NA	NA	HRC-containing canisters suspended in injection well	NA	NA	NA	HRC canisters in wells used with a recirculation system
Former Manufacturing Site	Walled Lake, MI	NA	HRC	NA	NA	NA	NA	NA	Geoprobe injection	NA	NA	NA	NA
Unocal Wichita	Wichita, KS	Pilot	HRC	NA	NA	NA	NA	NA	15 injection points	NA	NA	NA	NA
FMC Corporation Site	San Jose, CA	Pilot	HRC; 1040 lbs	NA	NA	None	150	20	6 direct-push points and 5 monitoring wells.	June 1999/1 year pilot test	Full scale planned	4 months after injection, 5, 6, 7 months after injection	Compared top-down to bottom-up injection and found no significant difference in vertical distribution of HRC
Hayden Island Cleaners	Portland, OR	Full	HRC; 1,680 lbs	6	14000	None	200	15	34 injection points in 2 rows	NA	Site closed	5 monitoring event performed sporadically through the first 13 months.	Closed to below groundwater MCLs.
Naval Air Station Dallas	Dallas, TX	Pilot	HRC	NA	NA	None	1500	10	NA	June 2000 - May 2001	Performance monitoring	NA	NA
Naval Air Warfare Center	Indianapolis, IN	Full	HRC	0	NA	None	NA	NA	Injection per Regenesis design	NA	NA	NA	NA
Hurlburt Field	Tallahasse, FL	Full	HRC; 6,000 lbs	6	36000	None	2500	30	24-25 direct injection points installed in a grid with 5 foot spacing. A total of 7 monitoring wells were installed for process monitoring	January 1999/NA	NA/NA	monthly for the first 2 months, quarterly thereafter	The goal of this application was to accelerate reductive dechlorination of TCE in the intermediate aquifer such that remedial goals will be reached in 5 years from the date of application. Degradation of TCE proceeded to completion until the HRC was depleted.
Industrial Site	NJ	Pilot	HRC; 1,080 lbs	NA	NA	NA	NA	NA	23 injection points using Geoprobe rig	NA	NA	NA	NA
Closed Industrial Facility	CO	Pilot	HRC; 1,200 lbs	NA	NA	None	NA	25	Polymer injected at nine locations using Strataprobe rig	September '99; 1 year	NA	NA	VOC data indicate reductive dechlorination was accelerated
Site 1, Santa Clara County	Santa Clara County, CA	Pilot	HRC and sodium lactate; 6 lbs/ft	17.5	NA	None	NA	NA	Injection by Geoprobe rig	NA	NA	NA	Additional injections 1.5 years later. Both HRC and fast HRC primer accelerated
Site 2, Santa Clara County	Santa Clara County, CA	Pilot	HRC - standard and primer; 3 lbs/ft	19	NA	None	NA	NA	Injection using Geoprobe rig. First, HRC-primer (fast-release) applied, and then the standard polymer (slow-release) is injected few inches away.	NA	NA	NA	Additional injections to source area after 9 months. Both fast and slow release HRC products were shown to stimulate anaerobic biodegradation of CAHs

TABLE 4.5 SUMMARY OF BIOREMEDIATION SYSTEM DESIGN (Continued)

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Depth (feet)					
HRC™ (Continued)													
Tosco Manufacturing Facility	Burien, WA	Full	HRC, 2,475 pounds	6.36	15750	None	4100	15	33 direct injection points. HRC was injected at a rate of 5 pounds per foot from 5 to 20 feet below ground surface.	November, 2000/ unknown	NA	Bimonthly for the first 7 months	Overall, PCE in 6 wells decreased an average of 70 percent. DCE, VC, and ethene concentration data were not published for this site.
Strip Mall Dry Cleaner	Kent, WA	Full	Full - 1,180 lb HRC	NA	NA	None	2000	NA	55 direct injection points and three monitoring wells.	NA	NA	Quarterly for the first 12 months, sporadically thereafter.	Closed with no-further-action.
Dayco Manufacturing Facility	Eldora, IA	Pilot	HRC, delivered via 4 4-foot canister implants installed successively in one well. The total mass of HRC emplaced was not published.	NA	NA	None	250	15	HRC was emplaced using 4 foot long perforated poly carbonate canisters. A total of 4 canisters were installed successively in four treatment event spanning 1 week. A total of 8 monitoring wells were used for process monitoring activities.	February 1998/Pilot test lasted 35 weeks	NA	Samples were collected at 2, 4, 8, 11, 24, and 35 weeks post emplacement	This application was designed to test emplacement of HRC from poly carbonate canisters as a method to develop a way to employ HC as a barrier wall. After 1 year, total VOC concentrations in shallow aquifer decreased by 50%. VOCs in deeper aquifer fluctuated over a greater range.
Moen Manufacturing Facility	Elyria, OH	Pilot	ORC and HRC tested in two identical side by side field applications	NA	NA	None	450	30	Two pilot test arrays consisting of 4 injection wells and 3 monitoring wells per array	July 1999/ 180 day pilot tests with design of full scale application to follow	Full scale application is currently in the design stage.	monthly during pilot testing	This application was a side by side comparison study of ORC to HRC for the dechlorination of DCE and VC. DCE and VC at this site result from natural degradation of TCE.
Springdale Drycleaners	Portland, OR	Pilot	HRC, 3,040 lb	NA	NA	NA	45000	3	A residual source area was treated with 5 injection points (80 lb HRC per point) and the downgradient dissolved phase plume area was treated with 22 injection points (120 lb HRC per point)	NA/2-3 years	OR DEQ is currently monitoring the pilot test application in consideration of a full scale application	Monitoring will occur quarterly for 2-3 years following application	NA
Reichhold Chemicals	Tacoma, WA	Pilot	HRC, 3,870 lb	NA	NA	NA	4300	5	A single line of 43 injection points were installed at 10 foot intervals. Two monitoring wells (10 feet upgradient and 10 feet downgradient) were used to monitor performance	NA/280 days	NA	monthly for the first 10 months.	This pilot test was designed to test the effectiveness of HRC to remediate phenolic contaminants in groundwater
Acton Mickelson Ordinance Facility	Hollister, CA	Pilot	HRC, 660 lb	NA	NA	NA	1200	4	25 injection points installed in a grid on 5 foot centers. 6 monitoring wells installed for process monitoring	NA/NA	NA	Process monitoring samples were collected 50 and 80 days after injection	Closed to below MCLs.
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Pilot	HRC, NA	NA	NA	NA	350	NA	HRC was injected into 30 locations installed in a line. A total of 15 monitoring wells were installed for process monitoring sampling.	NA/NA	NA/NA	Process monitoring samples were collected at 34, 57, 85, and 105 days following injection	This pilot test was designed to test the effectiveness of HRC to remediate nitrates and explosive compounds in groundwater.
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Pilot	HRC	NA	NA	NA	NA	NA	Barrier configuration	NA	Ongoing	NA	Evaluated effectiveness of HRC as a barrier type treatment in a high-flow aquifer
Manufacturing Facility	Crozet, VA	Pilot	HRC, 420 lb	21.43	9000	NA	50	6	3 injection wells spaced approximately 5 feet apart with one monitoring well installed approximately 10 feet downgradient from the injection wells.	NA/NA	Full scale HRC application is being considered	Monthly for the first 3 months, quarterly thereafter	HRC was shown to be effective at treating chlorinated solvents within the fractured bedrock system.
Manufacturing Facility	NJ	Pilot	HRC, 500 lb	7.5	3750	NA	4900	15	15 direct push points installed in a barrier configuration approximately 5 feet apart	NA/NA	NA	biweekly for the first 4 months	NA
Flemington Manufacturing Facility	Flemington, NJ	Pilot	HRC, NA	NA	NA	NA	NA	12	Three 3.5-inch by 4-foot long PVC canisters filled with gelled HRC were installed in a single 4-inch well. An unknown number of monitoring wells were installed for process monitoring.	NA/NA	NA/NA	biweekly for the first month, monthly thereafter	This application involved installing canisters of gelled HRC in a well as a slowly soluble and therefore longer term HRC source. This site is very similar to the Central US Manufacturing Facility application

TABLE 4.5 SUMMARY OF BIOREMEDIATION SYSTEM DESIGN (Continued)

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Depth (feet)					
HRC™ (Continued)													
Japanese Electrical Plant	Japan	Pilot	HRC, 600 lb	NA	NA	NA	500	7	7 injection points in two rows spaced approximately 13 feet apart. Row spacing was also approximately 13 feet. Two monitoring wells were installed, 1 upgradient and 1 downgradient.	NA/1 year	NA/NA	Quarterly	NA
Coopervision Manufacturing Facility	Scottsville, NY	Pilot	HRC, NA	NA	NA	NA	NA	33	NA	July 2001 / efforts to inject using direct push were unsuccessful	re-injection using mud rotary is planned	NA	NA
Invensys Control	Old Saybrook, CT	Pilot and Full	Pilot - HRC, NA Full - HRC, 11,000 lb	NA	NA	NA	NA	NA	Pilot - NA Full - 55 injection points in an unknown configuration, unknown number of monitoring points.	Pilot - December 1999/9 months Full - September 2000/NA	Full scale application is currently in the process monitoring stage	NA	Electron donor injection was a viable remedial approach for chlorinated VOCs in this low permeability application. 80% of PCE mass was removed.
Manufacturing Facility	Brighton, NY	Pilot	HRC, 500 lb	7.5	3750	None	560	NA	24 injection points installed in a grid with 5 foot spacing. 4 monitoring wells installed for process monitoring.	NA/NA	NA/NA	quarterly	Conditional Closure has been granted.
Arlington Cleaners	Arlington, TX	Full	HRC, 7,000 lb	4.457142857	31200	None	3000	15	45 direct injection points. 16 of the points were installed at a 15 to 30 degree angle to inject beneath a pre-existing structure. An unknown number of monitoring wells were installed for process monitoring.	May 2000 / Unknown	Process monitoring is ongoing	NA	During this application 1/3 of the injection wells were installed at a 15 to 30 degree angle to inject HRC under an existing building. Closure under the TNRCC VCP Program.
Edible Oils													
Former Zipper Manufacturing Facility	Newport News, VA	Pilot	Vegetable Oil; 4,800 lbs	NA	NA	NA	200	10	Geoprobe injection at 33 locations	April 2000	Evaluate full-scale remediation	NA	NA
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	Pilot, Full	Vegetable Oil	$0.50 per lb	5700	None	Approximately 3,000	22 to 32 feet bgs	Thirty three injection points installed with CPT	Pilot - June 1999 to June 2000, Full-Scale - July 2000 to present	Evaluating performance and system expansion	Semi-annual	NA
Site N-6, Former NSA Mid-South	Millington, TN	Pilot	Vegetable Oil	$0.22 per lb	10104	None	Approximately 350	45 to 85 feet bgs	6,100 gallons of soybean oil injected into 8 injection wells staggered at depths of 45 to 85 feet bgs.	August 2000 to present	Evaluating performance and system expansion	Semi-annual	Additional injection or redistribution of substrate may be required
Site SS-015, Travis AFB	Travis AFB, CA	Pilot, Full	Vegetable oil	$0.34 per lb	1100	None	Approximately 2,800	12 to 22 feet bgs	Thirty eight injection wells installed with CPT. 28 wells failed and were replaced with 25 direct injection points.	Full-Scale - December 2000 to present	Evaluating performance and system expansion	Semi-annual	NA
Site FF-87, Former Newark AFB	Newark, OH	Full	656 gallons of Vegetable oil emulsified with 2546 gallons of water	$0.47 per lb	2372	None	Approximately 900	17 to 25 feet bgs	Three injection wells in sand unit and three injection wells in lower silt unit	Full scale - September 2001 to present	Evaluating performance	Quarterly	IT is performing performance monitoring sampling and reporting
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	Pilot	3,600 gallons of Vegetable oil emulsified with 7,200 gallons of water	$0.39 per lb	10397	None	Approximately 400	40 to 50 feet bgs	Three injection wells in unconfined sand unit	Pilot - November 2001 to present	Evaluating performance and system expansion	Quarterly	One year results report will be submitted in May, 2003
Former Radiator Facility	IL	Pilot	330 gallons of straight vegetable oil	NA	NA	None	Approximately 80	5 to 15 feet bgs	Oil was injected into 1 shallow injection well	September, 2000	Evaluating performance	NA	Significant VC was produced within the treatment zone, corresponding with drastic decrease in TCE concentrations. Regulatory body is uncomfortable with going full scale due to VC production.

TABLE 4.5 SUMMARY OF BIOREMEDIATION SYSTEM DESIGN (Continued)

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Depth (feet)					
Edible Oils (Continued)													
Site SS-17	Altus AFB, OK	Pilot	Vegetable oil, 150 gallons as a 20% oil in water emulsion chased by 125 gallons of treated water.	NA	NA	NA	400	10	Six injection wells installed 5 feet apart in a barrier line configuration. Six new wells and 1 existing well were used for process monitoring.	December 2001	Process monitoring is ongoing	NA	6 injection wells installed in a barrier configuration with 5 foot well spacing.
OU-1 Landfill 3	Altus AFB, OK	Pilot	Vegetable oil, 50 gallons as a 20% oil in water emulsion chased by 110 gallons of treated water. 50 gallons of lactate and yeast extract.	NA	NA	Bromide, yeast extract, calcium chloride	400	NA	Two injection wells installed near an existing monitoring well.	NA	NA	NA	50 gallons of lactate and water from Site SS-17 (above) were injected into one of the two injection wells concurrent with the vegetable oil injection. Early results indicate bioaugmentation is not needed at this site.
Whiteman Air Force Base LF-08	Whiteman AFB, MO	Pilot	Vegetable oil, 575 gallons emulsified with 1600 gallons water	0.53	2390	None	4800	10	9 direction injection points and 10 monitoring wells installed.	July 2002 / 2 years	Process monitoring is ongoing	Semi-annually	Substrate was injected as an emulsion to increase the effective radius of influence and to improve the oil distribution in the subsurface.
SOLID SUBSTRATES													
Bark Mulch													
Building 301, Offutt AFB	Omaha, NE	Pilot and Full	Mulch	$20.00 per yd3 (estimated)	$10,960 (estimated)	None	Pilot: 100 linear feet Full: 400 linear feet	23 feet bgs	100-foot pilot biowall (23 feet deep) followed by a 400-foot (24 feet deep) full-scale biowall. Surface amendment pilot test.	Full - July 2001 to present (Full life span estimated to be approx. 10 yrs)	Evaluating performance	Bi-annual (approx.)	61 percent reduction in mean TCE concentration downgradient of biowall, 46 percent reduction in mean TCE concentration downgradient of surface amendment
OU1 Landfill 3	Altus AFB, OK	Full	Mulch	$10.00 per yd3 handling cost (estimated)	NA	Cotton Gin Compost and Sand	455 foot linear barrier wall	4 to 24 feet bgs	455-foot long by 24-foot deep by 1.5-foot wide barrier wall	July 2002 to present, estimated life-cycle of 10 years	Performance monitoring	Bi-annual	Elevated TOC observed 5 to 10 feet downgradient of biowall within two months
Naval Weapons Industrial Reserve Plant	McGregor, Texas	Pilot and Full	Primarily compost, with some cottonseed and vegetable oil	NA	NA	NA	NA	NA	Permeable Reaction Barrier Wall	NA	Performance monitoring	NA	Used gravel in trench to maintain permeability
Chitin													
Distler Brickyard Superfund Site	Louisville, KY	Pilot	Chitin; 325 lb	$3.5-4 (estimate)	$1,140 to $1,300	None	Approximately 150	38	Slurry with sand during hydraulic fracturing of low perm medium - FRAC RITETM method at 3 locations	Intended to last several years	Performance monitoring	NA	None
HYDROGEN													
Gaseous Hydrogen Injection													
Launch Complex 15	Cape Canaveral, FL	Pilot	Gaseous Hydrogen mix with 48% hydrogen: 130 ft3/day/well on day 1, 6 ft3/day/well (days 1-120), and 60 ft3/week/well (days 120+)	$0.05/scf	NA	None	Approx. 900	5 to 25 feet bgs	Low pulsed biosparging. Four sparge wells, 6 multi-level sample points, 20 other monitoring points.	18 months	Planning further testing at additional sites	Completed	Tracers show biological consumption of hydrogen. Methane competition did not hinder reductive dechlorination. Radius of influence 5 to 10 feet direct influence, 15+ feet indirect influence.
Gaseous Hydrogen Injection (Continued)													
Twin Cities Army Ammunition Plant	New Brighton, MN	Bench, Pilot	Membrane addition of hydrogen at concentrations of 62 to 855 nanomoles	$0.11/scf	NA	None	Approx. 27	NA	Gas-permeable membranes in three rows of 15 wells spaced 18-inches on center	Pilot system run for approximately 20 months	Pilot complete, preparing field transition plan	Weekly to Monthly	Hollow fiber membranes were able to deliver hydrogen near predicted levels for extended period of time. Presence of VC and ethene suggest that hydrogen was able to stimulate dechlorination of TCE, either directly or indirectly via acetate.

[a] NA indicates the data are not available.

Lactate was typically injected into shallow aquifers comprised of sand and silty sand. Reported maximum pre-treatment concentrations ranged up to 12 milligrams per liter (mg/L) of TCE for the Watertown Industrial Area Site (Table 4.3). TCE concentrations were reduced to a maximum of 1 mg/L at that site following treatment. While the data are limited, an increase in VC was only observed at the Watertown Industrial Area Site and the Naval Air Station (NAS) Point Mugu IRP Site. Data for ethene concentrations are even more limited, but an increase was observed at three sites (Bachman Road Residential Well Site, Cape Canaveral Facility 1381, and the NAS Point Mugu IRP Site), indicating that sequential dechlorination of chlorinated ethenes to ethene was achieved at those sites. As with most sites, geochemical data are limited (Table 4.4). Where reported, lactate addition lowered dissolved oxygen (DO) levels, oxidation-reduction potential (ORP), and sulfate concentrations. This is consistent with the objective of creating a more reducing environment suitable for reductive dechlorination to occur.

Lactate was typically injected directly into the subsurface through conventional injection wells (Table 4.5). Some form of groundwater extraction and recirculation was used at nine of the sites. The injection frequency ranged from weekly to monthly for time periods ranging from a single injection event (small pilot-scale) to 1 to 2 years (large full-scale). Total injection volumes typically ranged from a few hundred gallons for a limited-scale pilot test to up to 9,600 gallons for the Test Area North Site. Combination of lactate with groundwater extracted from downgradient well locations, and injection of the resulting solution into the treatment zone, is a common technique employed to improve the distribution of lactate in the subsurface.

Butyrate (or butyric acid) was applied at three sites included in the survey as part of the field demonstration for development of the RABITT protocol (Table 4.1). These pilot-scale treatability tests targeted chlorinated ethenes in shallow groundwater. The butyric acid was typically amended with yeast extract. TCE concentrations (Table 4.3) at the Alameda Point Building 360 Site and the Fort Lewis Gate Disposal Yard sites exhibited substantial declines.

Acetate was also applied at three sites. One early application in 1995 to 1996 at the Hanford Area 200 Site targeted CT and nitrate. The other two industrial applications (Gillette Company Site and a Manufacturing Site) targeted chlorinated ethenes. Bioaugmentation with methanol was implemented 3 months after the acetate injection at the Gillette Company Site, which eventually resulted in degradation of DCE and generation of VC and ethene.

4.1.2 Molasses and Refined Sugars

The most common dissolved substrate in the form of sugars is molasses. Molasses is a byproduct of refining sugars and is composed primarily of sucrose. The degradation of the sugars in molasses produces metabolic (fatty) acids and alcohols. Of the 14 sites in the survey, 6 pilot-scale tests were conducted. Six full-scale tests also were conducted, of which three were scaled up from pilot tests (Table 2.1). No bench-scale tests (e.g., site-specific microcosm studies) were encountered. With the exception of one DoE and two DoD sites, all of the molasses sites surveyed were at industrial facilities. The earliest application was at the Avco Lycoming Superfund Site in November 1995.

Lithologic descriptions indicate that molasses has been injected into a variety of water-bearing zones ranging from coarse-grained sands to silts and clays to fractured carbonate aquifers.

Concentration data (Table 4.3) show consistent declines in TCE and DCE. An increase in VC concentrations has been documented at several sites; however, these sites also have exhibited elevated ethene concentrations, indicating dechlorination was proceeding to completion.

In general, infiltration galleries or multiple injection points were installed using either conventional drilling techniques or DPT. Substrate is typically delivered in batch or periodic modes, and often the injection system is automated. Injected concentrations of molasses dissolved in water ranged from 5 percent to 66 percent. Often, the frequency and dosage of substrate addition was determined from process monitoring data.

Two of the sites (Washington Square Mall and a Former Plating Facility) are reported to be closed, indicating that remedial objectives were met. One other site, TRW Automotive, is reported to be in closure monitoring. Other sites are typically in ongoing performance monitoring.

Lactose (milk sugar) was applied at a former Municipal Waste Water Treatment Facility in New Hampshire. A pilot test was conducted in 1997, and the system was expanded to full-scale in 2000 (Schaffer *et al*., 2001). The substrate was applied as a proprietary blend of 70 percent lactose and 20 percent yeast extract dissolved in water. Concentrations of PCE, TCE, DCE, and VC have been reduced at the site as a result of the substrate addition. Full-scale implementation and monitoring are currently in progress.

Fructose was applied at Naval Support Activity (NSA) Mid-South by the Navy in March 2000. A pilot-scale recirculation system was employed. Concentrations of TCE were reduced, indicating that reductive dechlorination was stimulated. The pilot test is complete, and groundwater monitoring continues while a corrective measures study (CMS) is being prepared.

4.1.3 Other Dissolved Substrates

Sodium benzoate was used as a substrate at a New England Superfund Site (Turpie *et al*., 2000). A pilot test was initiated in January 1998 to explore the potential for enhanced bioremediation as a cost-effective alternative to a groundwater pump and treat system. Thirty injection wells were installed in three injection intervals in a barrier configuration. Degradation of DCE and VC was observed. The average calculated half-lives for DCE and VC over the first two years, based on ethene and ethane production, were 255 days and 48 days, respectively.

A methanol/acetate substrate was used in conjunction with bioaugmentation to stimulate anaerobic dechlorination of chlorinated ethenes at the Building 360 Site, Kelly AFB, TX. Both a bench- (microcosm) and pilot-scale technology demonstration test were performed, with the pilot test conducted in December 1999. A closed-loop circulation system was employed using three extraction wells and one injection well. The pilot test was monitored for approximately 1 year, and a 90-percent reduction in the maximum PCE concentration was reported (Majors *et al.,* 2001). A methanol/acetate/leachate substrate was used at the Rademarkt Site in the Netherlands. This was a pilot-scale test for chlorinated ethenes at an industrial site. Ten injection wells were installed upgradient of five extraction wells, and the re-circulated groundwater was amended with the substrate mixture.

It should be noted that higher-molecular-weight alcohols are fermented to acetate and hydrogen, while methanol does not degrade via a hydrogen-producing fermentation pathway (Gossett, 2002). This may be one reason that methanol is typically used in conjunction with other amendments.

Ethanol was used as a surfactant for flushing of DNAPL at the former Sages Dry Cleaner site in Florida (Jawitz *et al*., 2000). Residual ethanol was intentionally left in the groundwater system, and was observed to promote biodegradation.

4.2 SLOWLY-SOLUBLE SUBSTRATES

The most common semi- or slowly-soluble substrates used to stimulate anaerobic dechlorination are HRC™ and edible (vegetable) oils. HRC™ has been tested primarily at industrial sites and some DoD sites, while vegetable oils have been tested primarily at government facilities as an alternative lower-cost, slow-release substrate.

4.2.1 Hydrogen Release Compound (HRC™)

Data were collected for 35 sites where HRC™ was applied. HRC™ is a proprietary polylactate ester developed by Regenesis as a slow-release electron donor, and has been extensively applied at industrial sites as well as several DoD sites. Lactic acid is released in the subsurface environment upon hydration. Regenesis has indicated that HRC™ has been applied at 410 sites (Koenigsberg *et al*., 2002 and Koenigsberg, 2002). The number of HRC™ sites surveyed for this study is limited to those with currently available data or to those described in Regenesis case histories. Twelve additional sites are identified in Appendix B, but lack sufficient data to include in the survey tables.

Of the 35 sites in the survey, 26 were pilot-scale tests. Twelve full-scale tests were conducted, of which three were scaled up from pilot tests (Table 2.1). The scale of application for four of the sites was not determined. The earliest applications of HRC™ encountered during the survey were in January 1998 at the Watertown Industrial Area Site and an Industrial Site in Iowa (Table 4.1). In general, HRC™ has been used to treat chlorinated ethenes; however, contaminants targeted at some of the survey sites included chlorinated ethanes, chlorinated phenols, perchlorate, hexavalent chromium, and explosives.

Most often, HRC™ is injected directly into shallow contaminant plumes using DPT. Upwards of 175 direct-injection points were used at one site to inject approximately 5,000 pounds of HRC™ (Dixie Cleaners Site in Jacksonville, Florida). In some cases, HRC™ has been applied in canisters hung in a permanent well. Regenesis has also developed a fast acting HRC-primer which is injected first, and followed with the standard HRC™ product.

HRC™ has been successful at stimulating anaerobic dechlorination, and use of this product has been instrumental in developing regulatory acceptance for enhanced bioremediation. With one exception (Santa Clara County Site 2), reported concentrations of PCE and TCE decreased after application. Overall, Regenesis (Koenigsberg, 2002) reports 18 site closures, including 12 sites where MCLs were achieved, 1 site closed with a no-further-action decision, and 5 sites with some form of conditional closure.

4.2.2 Edible Oils (Vegetable Oil)

Refined soybean oil was used alone, or in combination with nutrient amendments, at 10 of the survey sites. Edible oils have been applied at eight DoD sites by the Air Force and Navy, as well as at two industrial sites. Vegetable oil injections have been performed at an additional seven sites(Appendix B), but insufficient data are available for inclusion in the survey. Earlier applications utilized injection of straight oil with a water push, but use of oil-in-water emulsions currently is the most common form of application. Vegetable oil injection has been used primarily as a source reduction measure, although use of vegetable oil permeable reaction zones or biowalls for plume containment and restoration also is a common configuration.

Chlorinated ethenes in groundwater were the targeted contaminant at all of the vegetable oil sites. Nine of the sites were pilot-scale tests or technology demonstrations, two of which were expanded to full-scale applications (Table 4.1). The tenth site was a direct full-scale application. System configurations have ranged from permanently-installed injection wells at depths of up to 85 feet, to direct injection through DPT probes at depths of less than 25 feet. Edible oils have generally been applied at sites with sandy sediments, although vegetable oil emulsions also have been injected into silty and clayey sediments (e.g., Travis AFB Site SS015 and Whiteman AFB Site LF-08). Volumes of vegetable oil injected ranged up to 6,100 gallons (47,000 pounds) at the Former NSA Mid-South, Tennessee (Table 4.5).

Each of the ten sites exhibited reductions in contaminant concentrations, although reductions at many sites have not been uniform or consistent for all of the chlorinated ethene compounds (Table 4.3). Most of the sites are currently being monitored for performance, and no sites have been approved for closure to date.

4.3 SOLID SUBSTRATES

Solid substrates that have been utilized for stimulating anaerobic dechlorination include tree mulch, compost, and chitin. Two approaches have been used for emplacing solid substrates. Tree mulch and/or compost was applied in permeable reactive biowalls at Offutt AFB, Altus AFB, and Naval Weapons Industrial Reserve Plant McGregor using a continuous trenching machine. Chitin was emplaced at the Distler Brickyard Site by hydraulic fracturing of the formation and injecting a slurry composed of chitin, sand, guar gum, and water. In both cases, the solid substrates are intended to be long-term sources of organic carbon. While both types of applications are intended to be one-time applications, additional fracturing and injection of a chitin slurry could be performed using the same injection well(s).

4.3.1 Mulch and Compost

To date, three mulch/compost applications have been implemented. Both a pilot- and full-scale shallow groundwater treatment system have been installed by the Air Force at the Building 301 Site at Offutt AFB, Nebraska. Based on encouraging results from Offutt AFB, the Air Force installed a second full-scale mulch biowall in June 2002 for a shallow groundwater plume at Altus AFB, Oklahoma. The Navy installed a compost and mulch biowall at the Naval Weapons Industrial Reserve Plant McGregor, Texas. This biowall was intended primarily to remediate perchlorate, but chlorinated ethenes also are being treated.

The mulch used at Building 301 was derived from tree trimming activities and was actively composting prior to emplacement. The pilot-scale biowall was 100 feet long by 23 feet deep by 1 foot wide and was installed in January 1999 (Haas *et al*., 2000). Depth to groundwater at the site is 3 to 10 feet below ground surface (bgs), and treatment is dependent on groundwater flow through the biowall. The shredded tree mulch was mixed with sand to maintain greater permeability within the biowall than in the adjacent formation, in order to prevent groundwater flow from circumventing the biowall. The mulch/sand mixture was emplaced using a continuous trenching machine, which was a cost-effective approach to substrate emplacement. Initial results of the pilot test indicated that reductive dechlorination of TCE to *cis*-1,2-DCE was stimulated. Based on the pilot-scale results, a 500-foot-long by 25-foot-deep by 1.5-foot-wide full-scale biowall was installed in July 2001.

Similarly, the biowall at Altus AFB used tree mulch from City of Altus maintenance operations mixed with sand and composted cotton gin waste. The Altus AFB biowall is 450 feet long by 24 feet deep by 1.5 feet wide, and is designed to intercept shallow groundwater migrating from a landfill at the base. Reduction of TCE to DCE was observed within 8 weeks of biowall installation. The Navy biowall in McGregor, Texas was composed primarily of compost and gravel, but three trench sections also were constructed using mulch, cottonseed oil, and vegetable oil. Significant reductions in perchlorate concentrations have been observed at this site.

Mulch applications are limited by the depth to which the substrate can be emplaced, and therefore, are suitable only for very shallow groundwater plumes. Current trenching technologies are limited to depths of approximately 30 feet in optimal lithologic conditions. In general, the greater the saturated thickness, and the sandier and less consolidated the sediments, the less depth can be achieved without the use of shoring. Both the Offutt AFB and Altus AFB sites are primarily underlain by silty clay, in which a trench will generally remain open without caving. The low hydraulic conductivity of these sediments also results in a longer residence time for contaminated groundwater in the trench reaction zone.

Mulch also was placed as a surface amendment during the Building 301 pilot study at Offutt AFB. A similar surface amendment pilot-test is being performed by the Air Force at Cape Canaveral Air Station (CCAS), Florida, although results for that test have yet to be published. Surface amendments rely on precipitation and infiltration to leach organic carbon into shallow contaminated groundwater. This application of mulch relies on a favorable water balance between precipitation, evapotranspiration, and infiltration. Therefore, climatic conditions should factor strongly into site selection.

Because site conditions for trenching or for a passive surface amendment has limited the available sites where these technologies can be applied, low-flow recirculation through surface amendments, lining of landfill excavations with bark mulch, and inclusion of a bark-mulch sub-layer in alternative landfill covers also have been proposed to expand the application of mulch or compost substrates.

4.3.2 Chitin

Chitin was selected as a low-cost solid substrate for enhanced anaerobic dechlorination at the Distler Brickyard Site in Louisville, Kentucky (Sorenson *et al*., 2002). The chitin was applied

by hydraulic fracturing using a chitin/sand/guar gum/water slurry. This application is unique in that it combines enhanced anaerobic dechlorination of chlorinated solvents through the addition of a solid organic substrate, with a conventional engineering technique to enhance the permeability of fine-grained, unconsolidated silt and clay sediments. The permeability of the sediments is enhanced by inducing a fracture to increase formation permeability during injection, and maintaining it after injection with a sand/chitin propant. The application likely will be applicable to consolidated sediments and carbonates as well.

At the Distler Brickyard Site, the chitin/sand/guar gum/water slurry was injected into a single well at three separate intervals ranging in depth from 25 to 38 feet bgs. A total of 325 pounds of chitin and 1,550 pounds of sand were successfully injected at high pressures (180 to 235 pounds per square inch [psi]) and relatively high rates (12 to 26 gallons per minute [gpm]) into the three intervals (Sorenson *et al*., 2002). Tiltmeter geophysical techniques were used to estimate fracture orientations. At each injection interval, a semi-horizontal fracture was induced and propagated up to a maximum effective radius of 13.9 feet. Formation permeability was maintained after injection by the sand/chitin propant.

The injection took place in September 2001, and only 8 months of performance monitoring data currently are available in the literature. Preliminary results of the pilot test indicate that reductive dechlorination of the primary CAH present, *cis*-1,2-DCE, has been stimulated. Elevated ethene concentrations suggest that dechlorination is proceeding to completion. Additional performance monitoring is planned to determine the overall effectiveness and longevity of chitin as an organic substrate in the groundwater system at the site.

4.4 APPLICATION OF GASEOUS HYDROGEN

Because microorganisms known to completely degrade PCE to ethene use hydrogen as an electron donor, addition of hydrogen is the most direct approach to stimulate anaerobic dechlorination. Although hydrogen is highly combustible, it is an inexpensive substrate that can be delivered safely with the proper engineering controls. Besides direct addition of hydrogen to groundwater, other methods to deploy hydrogen via hydrogen releasing compounds, hydrogen-generating electrodes, and permeable membranes also are being developed (Newell *et al.,* 2000 and 2001).

4.4.1 Direct Hydrogen Addition

The Air Force has conducted two pilot-scale treatability tests involving direct addition of hydrogen to groundwater (Newell *et al.,* 2000 and 2001). The first was a pull-push-pull test of groundwater contaminated with DCE at Offutt AFB, Nebraska in November 1998. One thousand liters of groundwater was extracted from a single well and amended with hydrogen and conservative groundwater tracers. The amended groundwater was re-injected and sampled periodically over a period of 48 hours. Concentrations of DCE decreased from 430 µg/L to non-detectable levels over the course of the test, indicating that anaerobic dechlorination of DCE was achieved.

Direct hydrogen injection into the subsurface also was conducted at Launch Complex 15 at CCAS, Florida. The pilot test utilized low-volume pulsed biosparging with hydrogen into a

sandy aquifer over an 18-month period. Both the treatment zone and a control zone were monitored to determine the effectiveness of the hydrogen addition. Concentrations of TCE and DCE decreased, while an increase in VC, ethene, and methane concentrations was observed. These data suggest that dechlorination proceeded to completion under methanogenic conditions. Based on these results, additional testing of hydrogen addition to stimulate anaerobic dechlorination is planned.

4.4.2 Membrane Addition

One site was encountered during the survey where a technology demonstration used permeable membranes for hydrogen addition. A pilot test was conducted at the Twin Cities Army Ammunition Plant in Minneapolis, Minnesota, for the Army. This is primarily a research project by the University of Minnesota (Novak *et al.*, 2002). Hydrogen was effectively delivered into groundwater by the pilot system, and a decrease in the concentrations of TCE was observed. A field transition plan is currently being developed.

SECTION 5

SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY OF PHASE I SITE SURVEY

Ninety three sites were surveyed for application of enhanced bioremediation by anaerobic dechlorination. Many additional sites were identified, but insufficient data were available to include them in the site survey tables at this time. ARCADIS (ARCADIS, 2002) has indicated that molasses has been applied at 88 completed or ongoing sites, 70 of which target chlorinated organic compounds. Of these 70 sites, 29 are full-scale applications. Regenesis has indicated that HRC™ has been applied at as many as 410 sites (Koenigsberg, 2002), although it is not known how many are bench-, pilot- or full-scale applications. In addition, there are likely many sites in Europe that have not been reported in the US literature. Therefore, substrate addition has been used to enhance anaerobic dechlorination at several hundred sites.

The goal of most of these applications was to stimulate anaerobic dechlorination by halorespiration of chlorinated solvents. The application of organic substrates for cometabolic anaerobic dechlorination is less well understood, and is generally not the targeted reduction pathway. In general, chlorinated ethenes were targeted for remediation. However, many sites have multiple types of CAHs present, and the use of anaerobic dechlorination for chlorinated ethanes, chlorinated methanes, chlorinated propanes, nitrates, and perchlorates will likely be applied more frequently in the future (ITRC, 2002).

The most common substrates used to date are HRC™, molasses, lactate, and edible oils. These compounds generally degrade or break down into short-chained metabolic (fatty) acids, which may be used directly as electron donors for reductive dechlorination by halorespiration, or more importantly are fermented to produce hydrogen as the electron donor. Direct injection of gaseous hydrogen also is being studied as a more direct approach to stimulating reductive dechlorination, and other solid substrates such as mulch or chitin have been applied.

Lactate has been used at both DoD and industrial facilities. Molasses has been primarily applied at industrial sites, but also has been applied at several DoD sites. HRC™ has been extensively tested at industrial sites and government sites, with many more applications than could be included in this study. The number of HRC™ applications at DoD sites is increasing. The use of edible oils has been primarily developed by the Air Force and Navy, but application at industrial facilities is becoming more common.

The physical properties of these substrates provide opportunities for a multitude of remedial approaches, substrate emplacement scenarios, and system configurations. The performance of

pilot-scale demonstrations prior to full-scale implementation is common. Surprisingly, the application of rigorous site selection criteria and bench-scale testing is less common. Review of the literature indicates that site selection criteria, such as the qualitative ranking system described in the RABITT Protocol (ESTCP, 1998), are often poorly defined.

In general, anaerobic dechlorination techniques for groundwater restoration are applied to achieve a combination of source reduction and plume containment. Many of the pilot-scale tests and technology demonstrations surveyed did not have a clearly-stated remedial objective, other than to demonstrate that a particular substrate could be used to stimulate reductive dechlorination. Substrate addition for anaerobic dechlorination is commonly used for source reduction, where groundwater restoration is achieved by reducing the contaminant flux from the source zone. Due to the difficulty in characterizing DNAPL sources, a grid or recirculation configuration is often employed to cover a contaminant plume source area or "hotspot." In contrast, substrate addition is used at many sites solely as a groundwater restoration measure. In these cases, the substrate may be distributed over a large portion of the contaminant plume, or may be configured as a barrier to intercept the plume.

Evidence that anaerobic dechlorination has been stimulated has been documented for all the substrates surveyed; however, universal success for any substrate to stimulate complete dechlorination or to meet remedial objectives is not yet apparent. For example, the ability of any given substrate to drive anaerobic dechlorination to completion (e.g., to production of ethene) may be a function of the native microbial populations or geochemical conditions that are present at a site. This suggests that, in many cases, site-specific characteristics could be as important as substrate selection in achieving remedial objectives. Clearly, site-specific conditions should be considered in substrate selection.

The majority of the sites surveyed lack sufficient performance monitoring data to report whether remedial objectives for the enhanced bioremediation application were achieved. This is likely due to the fact that the life-cycles of the remedial designs are often on the order of several months to years, combined with the fact that, within the last 2 years, there has been substantial growth in the rate at which enhanced bioremediation by anaerobic dechlorination has been applied. Therefore, the sheer number of applications may not be a good indication of the potential for success at a specific site.

5.2 RECOMMENDATIONS FOR PHASE II DETAILED SITE SURVEYS AND EVALUATIONS

The variety of substrates and delivery configurations employed for enhanced *in situ* bioremediation of chlorinated compounds via anaerobic dechlorination is daunting. RPMs faced with implementing anaerobic dechlorination and making these choices do not currently have a comprehensive guidance document. Furthermore, a comprehensive study that evaluates the differing anaerobic dechlorination techniques with respect to the success or failure of the applications completed to date has not been performed. This Phase I Site Survey provides a database that can be used as a first step to perform such a study. Therefore, it is recommended that this site survey effort be expanded to evaluate the degree of success of the technology to meet remedial objectives in order to support development of an anaerobic dechlorination guidance document.

5.2.1 Bioremediation Guidance Document

Because anaerobic dechlorination is being applied at multiple DoD sites across the country, the Navy and the Air Force Center for Environmental Excellence (AFCEE) are cooperating to develop a guidance document for DoD RPMs and their contractors to use when considering enhanced bioremediation as a remedial alternative for chlorinated compounds in groundwater. While other potential applications may be identified, this guidance document will be limited to the use of substrates to stimulate *in situ* reductive dechlorination of chlorinated compounds in groundwater. Representatives from other DoD and government agencies will be asked to participate in review capacities.

AFCEE/ERT is currently funding a delivery order to prepare the guidance document, to solicit contributions from technical experts, and to convene an independent review committee. ESTCP's Phase II activities that will contribute to this guidance document include a literature review and evaluation of the state of the industry, lessons learned from prior applications, a cost survey, and cost estimating software development.

5.2.2 Phase II Scope of Work

In order to support the guidance document, implementation of Phase II has been recommended to further evaluate selected Phase I sites for the purpose of providing a basis for comparison and guidance on the selection and use of anaerobic dechlorination techniques. In particular, a section on "lessons learned" will be the basis for determining which dechlorination technologies will most likely lead to successful and cost-effective remediation of chlorinated solvents in the subsurface at a particular site.

A number of sites will be selected for further in-depth evaluation. Evaluation of these sites should include, but not be limited to:

- Site selection criteria;
- Rationale for substrate and amendment selection;
- Rationale for substrate mass and design parameters;
- Efficiency of methods employed to distribute the substrate in the subsurface;
- Optimal frequency of substrate addition to obtain complete dechlorination, and the need for bioaugmentation;
- Operation and maintenance requirements;
- Performance monitoring strategies;
- Life-cycle costs to apply a particular substrate and configuration;
- Timeframe to achieve remedial objectives; and
- Reasons why differing anaerobic dechlorination applications met or did not meet project objectives.

Results of this Phase II evaluation will provide a basis for comparison and guidance on the selection and use of anaerobic dechlorination techniques. Cost data will be collected and compiled for select Phase II sites to develop a cost estimation tool. Life-cycle costs will be obtained and broken down into capitol and operation and maintenance cost components including design, permitting, system installation, substrate addition, operation and maintenance, performance monitoring, reporting, and regulatory compliance. The cost estimation tool will be developed using standardized costs where appropriate. The ability of an application to successfully meet remedial objectives also will be critically examined when evaluating life-cycle costs.

SECTION 6

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APPENDIX A

PROJECT CONTACT INFORMATION

PROJECT CONTACTS

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APPENDIX B

PHASE I SITE SURVEY DATABASE

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description
Lactate												
Bachman Road Residential Well Site	Oscoda, MI	Yes	TCE, DCE, VC	Industrial	Michigan DEQ	Groundwater remediation	Pilot	September 2000	John Lenvay, Univ of San Francisco Erik Petrovskis, HSI Geotrans	Ongoing	Lendvay *et al*., 2001a Lendvay *et al*., 2001b Abriola *et al*., 2001b	Relatively uniform glacial outwash sands and gravels approximately 17 feet thick and underlain by a thick, dense clay unit. The sand and gravel unit is a fining upward sequence with the gravel beds present immediately above the clay unit interface.
Area 6, Dover AFB	Dover AFB, DE	Yes	TCE, DCE	Air Force	USEPA, Delaware DNREC	Technology demonstration; groundwater remediation	Pilot	April 1998	David Ellis, DuPont 302-892-7445	Implemented Bioaugmentation, Pilot Test Complete	USEPA, 2000a	Sand with varying amounts of clay, silt and gravel. Fine-grained clay and silt to 5-feet bgs underlain by more permeable layer of silt and sand.
Former Drycleaning Facility	WI	Yes	PCE	Industrial	NA	Source reduction by 50%	Full	August 1997	Stacey Koch, RMT Inc.	NA	Koch and Rice, 2001	20-feet of glacially deposited sand and gravel overlying sandstone bedrock
Former Manufacturing Site	NJ	No	NA	Industrial	NA	NA	NA	NA	NA	NA	NA	
Test Area North (TAN), INEEL	ID	Yes	TCE	DoE	NA	Groundwater remediation	Full	Pilot - November 1998	Kent Sorenson, Northwind Environmental	Process monitoring is ongoing	Sorenson, 2000; Sorenson, 2002	Fractured basalt bedrock. Waste water was injected between 200 and 475 feet below ground surface. The fractured basalt sill is bounded on the bottom by a thick silty aquitard.
Ogallala Superfund Site	Ogallala, NE	Yes	PCE, TCE	Industrial	Nebraska DEQ, EPA Region VII	Technology assessment	Pilot	36262	Vicki Murt, Nebraska Department of Environmental Quality	Process monitoring is ongoing	Nebraska DEQ, 2000, Murt *et al.* , 2000	Approximately 26 to 27 feet of fine to medium grained sand underlain by calcareous silty clay.
NAS Fallon	Fallon, NV	Yes	PCE, TCE, DCE	Navy	NA	Compare enhanced and intrinsic biodegradation rates	Pilot	1998	Victor Magar, Battelle	NA	Magar *et al.*, 1999	Approximately 4-feet of sandy soil underlain by approximately 2-feet of clay-rich silts and sands. Bottom is sandy silt, and clay layer greater 20 feet thick.
Seal Beach Site 40	CA	No	NA	Navy	NA	Groundwater remediation to potable water standards	Pilot	NA	Kent Sorenson, Northwind	Ongoing	NA	NA
Tennessee Air National Guard	TN	No	NA	DoD	NA	Groundwater remediation to reduce total VOC to < 500ppb	Pilot	Planned Spring 2002	Kent Sorenson, Northwind	Planned spring 2002	NA	NA
Black's Drycleaner	OR	No	PCE, TCE	Industrial	NA	Technology demonstration	Pilot	September, 2001	Kent Sorenson, Northwind	NA	NA	NA
Pinellas Northeast Site	Largo, FL	No	NA	NA	NA	NA	Pilot	NA	NA	NA	US Department of Energy, 1998	NA
Former PEC Industries Site	Orlando, FL	Yes	PCE, TCE, DCE, VC	Industrial	NA	Groundwater remediation	Pilot	2001	NA	NA	Dean *et al*., 2001	The surficial aquifer consists of three sand units separated by sandy clay and clayey sand aquitards. The upper most sand unit extends from ground surface to approximately 10 to 15 feet below ground surface. The remaining two sand units and the intervening sandy clay units are approximately 5 to 10 feet thick. The entire surficial aquifer is perched above a dense clay unit of unknown thickness.
Cape Canaveral Facility 1381	Cape Canaveral, FL	Yes	TCE, DCE, VC	Air Force	Florida DEP	Treatability study	Microcosm, Pilot	March 1999	Jeff Morse, Battelle	Demonstration completed	AFRL *et al*, 2001	Poorly sorted coarse to fine sands and shell material to 35 feet. From 35-50 ft bgs, the sands show a decrease in grain size and silt and clay content increases. A continuous clay unit is present from 48 - 51 ft bgs.
Watertown Industrial Area	Watertown, MA	Yes	TCE, DCE	Industrial	Massachusetts DEP	Feasibility study	Pilot	July, 1997	Willard Murray, Harding Lawson Associates	Feasibility study was ongoing as of March, 2000	Murray *et al.* , 2000; Murray *et al.* , 2001	Industrial site adjacent to river, 20 ft of silty sand on top of thin till and bedrock

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Lactate													
Bachman Road Residential Well Site	Oscoda, MI	NA	8	Unconfined sandy gravel aquifer perched above a dense clay aquitard.	16 - 150	NA	NA	1,800	Industrialized area - source unknown	TCE - 0.13 DCE - 0.19 VC - 0.25 Ethene - ND	TCE - ND DCE - ND VC - ND Ethene - 0.36	*cis*-1,2-DCE, VC	Contaminant concentration reduction, as measured in one monitoring well, was nearly 100% for TCE, DCE, and VC.
Area 6, Dover AFB	Dover AFB, DE	NA	10 - 12	Unconfined aquifer made of 3 zones; groundwater occurs in bottom 2 zones of medium sand. Saturated thickness is 38 ft.	60	0.001	30	140	Waste disposal facility	PCE - 0.046 TCE - 7.5 DCE - 2 VC - 0.034	PCE - ND TCE - 0.075 DCE - 0.045 VC - 0.020	Arsenic, cadmium	As of March 1998, 98.5% of TCE and DCE in groundwater were converted to ethene and 75% to 80% of the TCE and DCE mass had been recovered as ethene.
Former Drycleaning Facility	WI	NA	10	Unconfined aquifer of glacial deposits, 20 ft thick. Surficial weathered bedrock is also impacted.	0.37 - 4.5	NA	NA	NA	Former drycleaning facility	PCE - 0.52 TCE - ND DCE - ND	PCE - 0.22 TCE - 0.003 DCE - 0.028	NA	PCE concentrations were reduced by approximately 58% while TCE and DCE concentrations increased form below method detection limits to concentrations greater than the Federal MCL for each contaminant.
Former Manufacturing Site	NJ	NA	1.5	Unconfined aquifer.	NA	NA	NA	NA	NA	NA	NA	NA	NA
Test Area North (TAN), INEEL	ID	NA	200	Impacted fractured basalt aquifer from about 200 ft to about 475 ft bgs.	NA	NA	NA	NA	Former wastewater and sanitary sewage injection well	TCE - 3.2	TCE - < 0.005	NA	Within 6 weeks from the start of lactate injection nearly 100% of TCE concentrations in groundwater had been dechlorinated to DCE and complete dechlorination was occurring within 4 months.
Ogallala Superfund Site	Ogallala, NE	NA	11 with season fluctuations to 2	Unconfined aquifer perched above the Ash Hollow silty clay.	450 - 612	0.002	35 - 35	1,095 - 1,280	NA	PCE - 0.03 TCE - ND DCE - ND VC - ND	PCE - 0.06 TCE - 0.001 DCE - 0.14 VC - NA	NA	Contaminant reduction calculations could not be performed due to the limited availability of analytical data.
NAS Fallon	Fallon, NV	NA	8 - 10	Shallow, unconfined, perched aquifer.	NA	0.0004	NA	NA	Former open fire-training pit	PCE - 0.680 TCE - 0.915 DCE - 0.866 VC - 0.0043	PCE - <0.025 TCE - ~0.1 DCE - ~0.250 VC - 0.0015	1,1-DCE, Benzene, Toluene	Contaminant concentration reduction in groundwater ranged from a minimum 65% in the case of VC to a maximum of 99.7% in the case of PCE.
Seal Beach Site 40	CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Analytical data was not provided for this site.
Tennessee Air National Guard	TN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Analytical data was not provided for this site.
Black's Drycleaner	OR	NA	NA	NA	NA	NA	NA	NA	Industrial dry cleaning facility	NA	NA	NA	Analytical data was not provided for this site.
Pinellas Northeast Site	Largo, FL	NA	NA	NA	NA	NA	NA	NA	Former nuclear weapon components manufacturer	NA	NA	NA	Analytical data was not provided for this site.
Former PEC Industries Site	Orlando, FL	NA	30 - 35	Primary contamination occurs in confined intermediate zone. Pumping to enhance flow in the unit.	NA	NA	NA	NA	Printed circuit board manufacturer. VOC contamination present beneath a former drum storage area.	PCE - 0.043 TCE - 0.017 DCE - 8.1 VC - 0.112 Ethene - 0.003	NA	1,1-DCE, CA	As of May 2001, substrate injection had not been performed at this site.
Cape Canaveral Facility 1381	Cape Canaveral, FL	NA	4 - 7	Unconfined aquifer 35 ft thick.	88.7	NA	NA	77	Cleaning and degreasing operations at the Ordnance Support Facility.	TCE - 1.97 DCE - 11.1 VC - 1.25 Ethene - < 0.2	TCE - ND DCE - 0.97 VC - 0.625 Ethene - 1.75	NA	RABITT protocol slightly modified because Florida's UIC regulations do not allow for reinjection of contaminated groundwater. Reduction of TCE, DCE, and VC by 88.7%, 90.6%, and 66.3%, respectively
Watertown Industrial Area	Watertown, MA	NA	8 - 12	Unconfined aquifer.	0.00006	NA	NA	0.005	Former metal degreasing shop	PCE - 1.5 TCE - 12.0 DCE - 3.5 VC - 0.1 Ethene - N/A	PCE - 0.1 TCE - 1.0 DCE - 3.0 VC - 1.0 Ethene - N/A	NA	Contaminant concentration reduction ranged from 7% in the case of PCE to 92% in the case of TCE. Contaminant mass reductions were measured in a single well (IN-2).

BIOREMEDIATION MANUAL
Summary of Information on Sites Implementing Enhanc

		Total Organic Carbon		Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane	
Site Name (Sorted by Substrate)	Site Location	Maximum Pre-Treatment	Maximum Post-Treatment	Range Pre-Treatment	Range Post-Treatment	Range Pre-Treatment	Range Post-Treatment	Range Pre-Treatment	Range Post-Treatment	Range Pre-Treatment	Range Post-Treatment	Range Pre-Treatment	Range Post-Treatment	Range Pre-Treatment	Range Post-Treatment	Range Pre-Treatment	Range Post-Treatment
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mV)	(mV)	(su)	(su)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Lactate																	
Bachman Road Residential Well Site	Oscoda, MI	NA[a/]	NA	0.5 to 2	< 0.5	Approximately -200	Approximately +100	7.1 to 7.6	7.1 to 7.6	NA	NA	NA	NA	NA	NA	NA	< 3.42
Area 6, Dover AFB	Dover AFB, DE	NA	18	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Former Drycleaning Facility	WI	NA	NA	4.2 - 6	0.33 - 2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Former Manufacturing Site	NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Test Area North (TAN), INEEL	ID	NA	NA	0.1 - 2.6	0 - 0.3	+44 to +310	-230 to +260	NA	NA	0.9 - 2.6	0.1 - 2.3	NA	NA	34 - 41	3 - 41	NA	NA
Ogallala Superfund Site	Ogallala, NE	2.4	210	NA	NA	NA	NA	NA	NA	11	6	NA	NA	134	< 10	NA	11,000
NAS Fallon	Fallon, NV	NA	NA	NA	NA	-250	-400 to -250	7.6 to 9.1	NA	< 0.09	NA	NA	NA	809 to 8,890	NA	NA	NA
Seal Beach Site 40	CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tennessee Air National Guard	TN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Black's Drycleaner	OR	< 1	300	NA	NA	NA	NA	NA	NA	< 1	< 1	NA	NA	13.9	1.8	< 1	12
Pinellas Northeast Site	Largo, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Former PEC Industries Site	Orlando, FL	18 - 46	NA	< 1.1	NA	-190 to +120	NA	5.1 to 6.0	NA	< 0.02 - 0.08	NA	0.5 to 13.7	NA	0 to 78	NA	3.1 to 3,325	NA
Cape Canaveral Facility 1381	Cape Canaveral, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Watertown Industrial Area	Watertown, MA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.2 - 0.3	0.05 - 0.1

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area: Surface Area (sq. ft)	Treatment Area: Thickness (feet)	System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
Lactate													
Bachman Road Residential Well Site	Oscoda, MI	Pilot	Lactate	NA[a/]	NA	Bioaugmentation, nitrogen, phosphorous	270	8	Two injection wells; one extraction well; network of monitoring points around the plot. Lactate was injected as a 6% solution in water.	September 2000; 140 days injection	Ongoing	NA	NA
Area 6, Dover AFB	Dover AFB, DE	Pilot	Sodium lactate	NA	NA	Bioaugmentation with a microbial culture from the DOE Pinellas Site, ammonia, and phosphate	2,400	5	3 injection wells, screen 38-48' bgs. Closed loop recirculation cell w/ 3 recovery wells. Cyclic injection of nutrients and unamended GW.	April 1998 to June 1999 - Pilot	Implemented Bioaugmentation, Pilot Test Complete	NA	NA
Former Drycleaning Facility	WI	Full	Lactate; 200 mg/L	NA	NA	Amended with 2 mg/L yeast extract, sodium sulfite	NA	NA	Injection wells. The four injections after the first were made under pressure to reduce biofouling.	August '97 - April 2000	Performance monitoring	About every 6 weeks	NA
Former Manufacturing Site	NJ	NA	Sodium lactate	NA	NA	Amended with yeast extract	NA	NA	Injection into well	NA	NA	NA	NA
Test Area North (TAN), INEEL	ID	Pilot	9600 gallons of Sodium lactate	$ 0.70 to $0.80	Approximately $54,000	Sodium bromide	700	200	300 gallons of sodium Lactate was injected weekly for 8 months.	November 1998 - current	Ongoing	Biweekly for the first 9 months, sampling frequency unknown after the 9 month point	NA
Ogallala Superfund Site	Ogallala, NE	Pilot	Sodium lactate injected at about 60% lactate in water in 3 to 4 week intervals over 10 months.	NA	NA	Potassium Bromide	Approximately 420	10	One extraction well, two injection wells, 6 monitoring wells installed. Substrate injection was performed concurrently with groundwater extraction from the downgradient extraction well to form a closed recirculation system.	April 1999 to current	Site groundwater monitoring continues to date.	Monthly for the first year, approximately annually thereafter.	NA
NAS Fallon	Fallon, NV	Pilot	Lactate	NA	NA	Yeast extract, vitamins	NA	NA	Recirculation with nutrient addition	500 days	NA	NA	NA
Seal Beach Site 40	CA	Pilot	Sodium lactate	$0.70 to $0.80	NA	NA	NA	NA	Single well injection, weekly to monthly	NA	NA	NA	NA
Tennessee Air National Guard	TN	Pilot	Sodium lactate	$0.7-0.8	NA	NA	NA	NA	Multiple manifold wells, bimonthly	NA	NA	NA	NA
Black's Drycleaner	OR	Pilot	Sodium lactate	$0.7-0.8	NA	NA	NA	NA	Single well injection, one time for demo	NA	NA	NA	NA
Pinellas Northeast Site	Largo, FL	NA	Sod. Benzoate + sod. Lactate + methanol	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Former PEC Industries Site	Orlando, FL	Pilot	Sodium Lactate	NA	NA	Ammonia and ortho-phosphate	Approximately 12,000	10	Each treatment cell consists of 4-5 extraction wells on cell perimeter around central injection well.	2001 (planned)	The injection phase of this pilot test was planned for 2001, monitoring was to have been conducted through 2002.	NA	The well installation and baseline monitoring phases have been completed as of May 2001. The injection phase was scheduled for 2001 while monitoring was to be extended through 2002.
Cape Canaveral Facility 1381	Cape Canaveral, FL	NA	Lactic Acid; 7.6 L/min at 3mM	NA	NA	None	340	10	Two communicating (recirculation) wells, 13 tri-level groundwater monitoring probes, and upgradient and downgradient monitoring wells.	149 days	Demonstration Complete	Biweekly	Rapid dechlorination of TCE and cDCE to VC, followed by slower subsequent dechlorination of VC to ethene under sulfate and methanogenic conditions
Watertown Industrial Area	Watertown, MA	Pilot	Lactic acid	NA	NA	Amended with ammonia chloride, tripolyphosphate, yeast extract, and sodium hydroxide	NA	NA	System of injection and recirculation cells	NA	NA	NA	After 8 months of anaerobic operation, the system was converted to an aerobic circulating cell for 3 months.- ORC,methane addition => 70% reduction of total ethenes in 11 months.

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description
Lactate (Continued)												
Aerojet Superfund Site	CA	Yes	TCE	Industrial	NA	Technology demonstration	Pilot	September, 2000	Evan Cox or David Major, Geosyntec Consultants	NA	Cox *et al*., 2002	NA
Naval Air Station Point Mugu IRP Site 24	CA	Yes	TCE, DCE, VC	Navy	NA	Technology demonstration	Pilot	December, 1998	Daniel Leigh, IT	Pilot test was completed in December 1999.	Leigh *et al*., 2002	The upper unconfined aquifer consists of approximately 10 feet of sand and gravel overlying approximately 4 feet of clay. The lower confined aquifer consists of a massive sand unit underlying the clay unit.
Weyerhauser Sycan Maintenance Shop	Beatty, OR	Yes	PCE, TCE	Industrial	NA	Feasibility study	Pilot	NA	Sanjay Vancheeswaran, CH2M Hill	NA	Vancheeswaran *et al*., 2001	The unconfined aquifer matrix consists of sandy silt to a depth of approximately 9 feet below ground surface. Underlying the upper sandy silt is a silty clay aquitard approximately 10 feet thick. The lower aquifer matrix consists of approximately 15 feet of silty sand underlying the upper aquitard and overlying the massive clays of the lower aquitard.
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	Yes	1,1,2,2-PCA, TCE	DoD	NA	Treatability study	Pilot	NA	Andrew Jackson, Texas Tech University	NA	Jackson *et al.* , 2001	NA
Lauderick Creek Area of Concern, Southern Plume Area, Aberdeen Proving Ground	MD	No	1,1,2,2-PCA	DoD	NA	Treatability study	Pilot	NA	Andrew Jackson, Texas Tech University	NA	Jackson *et al*., 2001	NA
Lauderick Creek Area of Concern, Southeast Plume Area, Aberdeen Proving Ground	MD	No	1,1,2,2-PCA	DoD	NA	Treatability study	Pilot	NA	Andrew Jackson, Texas Tech University	NA	Jackson *et al.* , 2001	NA
Lauderick Creek Area of Concern, North Plume Area, Aberdeen Proving Ground	MD	No	1,1,2,2-PCA	DoD	NA	Treatability study	Pilot	NA	Andrew Jackson, Texas Tech University	NA	Jackson *et al*., 2001	NA
Southern US Industrial Site	Unknown	Yes	PCE	Industrial	NA	Groundwater remediation	Full	March 1998	Sami Fam Innovative Engineering Solutions Inc.	Ongoing	Fam *et al*., 2001	Overburden generally consists of 10 to 20 feet of silty clay with slightly more permeable silty sand seems. The silty clay to silty sand overburden overlies competent limestone bedrock.
Molasses												
Avco Lycoming Superfund Site	Williamsport, PA	Yes	TCE	Industrial	USEPA	Groundwater remediation	Pilot, Full	Pilot: November 1995 Full: January 1997	Daniel Jacobs, ARCADIS 215-752-6840	Ongoing	National Priorities List Site Narrative, 1990; Horst *et al*., 2000; USEPA, 2000	Glacial sandy silt overburden (25') overlying fractured limestone bedrock
Cedarburgh Drycleaners	Cedarburgh, WI	Yes	PCE, TCE, DCE	Industrial	WDNR	Soil and groundwater remediation	Full	NA	Jim Drought, ARCADIS 414-276-7742	NA	State Coalition for Remediation of Drycleaners (Cederburgh, Wisconsin)	Poorly drained silty clay topsoil with little sand and gravel (1-4') Silty clay and clayey silts (4-16') Silty clay with trace sand and gravel (15-39') overlying silty find sands
Industrial Site	Central Ohio	Yes	DCE, VC	Industrial	NA	Contaminant mass reduction in a downgradient groundwater plume	Pilot	Phase I: November 1996 Phase II: September 1998 Phase III: June 1999	Jim Peeples, formerly Parsons	NA	Peeples *et al*., 2000	Sand and gravel
Washington Square Mall	Germantown, WI	Yes	PCE	Industrial	Wisconsin DNR	Source reduction with residual natural attenuation	Full	August 1998 - Pilot March 1999 - Full	Michael Maierle, ARCADIS 414-276-7742	Site closed	Maierle and Cota, 2001	Approximately 14 feet of clay and silt overlying a 2 to 5 foot thick saturated silt and sand bed, clay till aquitard below the saturated silt/sand bed

Site Name (Sorted by Substrate)	Site Location	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Lactate (Continued)													
Aerojet Superfund Site	CA	NA	NA	NA	NA	NA	NA	NA	Aircraft manufacturing facility, plating	TCE - NA DCE - NA VC - NA Ethene - NA	TCE - < 0.005 DCE - NA VC - NA Ethene - NA	NA	TCE concentrations were reduced by nearly 100% 125 days of injection.
Naval Air Station Point Mugu IRP Site 24	CA	NA	5	Shallow unconfined aquifer underlain by a thin but continuous aquitard and a large confined aquifer.	NA	0.001	NA	NA	Oil/water separator	TCE - 1.7 DCE - 0.75 VC - 0.001 Ethene - NA	TCE - < 0.005 DCE - < 0.005 VC - 0.015 Ethene - 0.020	NA	Within approximately 180 days TCE and DCE concentrations had been reduced by nearly 100% at one well. However VC concentrations increased by a factor of 15 within the same time period.
Weyerhauser Sycan Maintenance Shop	Beatty, OR	NA	4	Upper perched aquifer overlying a thick and continuous silty clay aquitard. Lower aquifer confined by the upper aquitard and bottomed by the dense clays of the lower aquitard.	NA	NA	NA	NA	Maintenance facility for railroad cars and engines	PCE - 1.7 TCE - 0.45 DCE - 3.6 VC - 0.09 Ethene - NA	PCE - 0.2 TCE - 0.16 DCE - 1.4 VC - 0.09 Ethene - NA	1,1,1-TCA, Trichlorofluoroethene (TCFE) used as a tracer due its chemical similarities to PCE and TCE	The PCE, TCE, and DCE concentrations were reduced by approximately 88%, 64%, and 61% respectively while the VC concentration stayed about the same.
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	NA	3	Shallow surficial aquifer which discharges to a nearby surface water body.	NA	NA	NA	NA	Chemical weapons training	1,1,2,2-PCA - 20 TCE - 1 DCE - ND VC - ND	1,1,2,2-PCA - 3.5 TCE - 1.8 DCE - 3.9 VC - ND	1,1,1-TCA, 1,2-DAC, chloroethane, DCE, VC	Within 14 weeks the 1,1,2,2-PCA concentration at one well was reduced by 83% while the TCE and DCE concentrations increased.
Lauderick Creek Area of Concern, Southern Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Analytical data was not provided for this site.
Lauderick Creek Area of Concern, Southeast Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Analytical data was not provided for this site.
Lauderick Creek Area of Concern, North Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Analytical data was not provided for this site.
Southern US Industrial Site	Unknown	NA	5	NA	NA	NA	NA	NA	Industrial Use	NA	NA	NA	Analytical data was not provided for this site.
Molasses													
Avco Lycoming Superfund Site	Williamsport, PA	NA	10 - 15	Contaminated aquifer 10-12' thick	0.2 - 24	NA	NA	7.3 to 840	Aircraft manufacturing facility, plating	TCE - 0.048 DCE - 0.010 VC - < 0.001	TCE - 0.0014 DCE - 0.002 VC - < 0.001	Hexavalent chromium, cadmium	NA
Cedarburgh Drycleaners	Cedarburgh, WI	NA	3 to 5	NA	28 (clean, silty sand) 0.03 (silt, silty clay)	0.03 - 0.06	NA	NA	Drycleaning facility	PCE - 6.8 TCE - 0.810 DCE - 1	NA	1,1-DCE	NA
Industrial Site	Central Ohio	NA	11	Shallow unconfined aquifer	110	0.02	NA	NA	Lagoon area used to contain metal machining liquid wastes	DCE - 0.265 VC - 0.015	DCE - 0.025 VC - 0.004	Fuels and cutting oil constituents	After 6 months of process monitoring, average DCE and VC concentrations had been reduced by 91% and 73% respectively.
Washington Square Mall	Germantown, WI	NA	12 to 14	Groundwater occurs within the 2 to 5 foot thick silt/sand bed at a depth of approximately 14 to 19 feet bgs	0.06	NA	NA	NA	NA	PCE - 1.5 TCE - 0.1 DCE - < 0.1 VC - ND Ethene - ND	PCE - ND TCE - ND DCE - 0.4 VC - 0.1 Ethene - 0.35	NA	NA

Site Name (Sorted by Substrate)	Site Location	Total Organic Carbon		Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane	
		Maximum Pre-Treatment (mg/L)	Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)
Lactate (Continued)																	
Aerojet Superfund Site	CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Naval Air Station Point Mugu IRP Site 24	CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.7	0.005	< 1	0.75
Weyerhauser Sycan Maintenance Shop	Beatty, OR	NA	NA	NA	NA	+25	-400 - -520	6.9	5.4	NA	NA	NA	NA	NA	NA	NA	NA
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lauderick Creek Area of Concern, Southern Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lauderick Creek Area of Concern, Southeast Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lauderick Creek Area of Concern, North Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Southern US Industrial Site	Unknown	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Molasses																	
Avco Lycoming Superfund Site	Williamsport, PA	2	40	0.8 to 5	NA	45 to +239	-120 to +116	NA	5.9 to 6.8	NA	NA	NA	<1 to 20	NA	<2.5 to 170	NA	NA
Cedarburgh Drycleaners	Cedarburgh, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Industrial Site	Central Ohio	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Washington Square Mall	Germantown, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area Surface Area (sq. ft)	Treatment Area Thickness (feet)	System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
Lactate (Continued)													
Aerojet Superfund Site	CA	Pilot	Lactic acid	NA	NA	Bioaugmentation with a commercially produced microbial augment (KB-1)	NA	NA	NA	September 2000/NA	NA	NA	NA
Naval Air Station Point Mugu IRP Site 24	CA	Pilot	1020 gallons of lactic acid as a 88% in water mixture	NA	NA	None	5,000	10	One extraction well, one injection well and 5 monitoring wells. Groundwater was circulated in a closed loop between the extraction well and the injection well.	December 1998, 1 year	Pilot Test Complete/ follow up unknown	Biweekly for the first 12 months.	NA
Weyerhauser Sycan Maintenance Shop	Beatty, OR	Pilot	Lactic Acid	NA	NA	Potassium Bromide, TCFE	80	10	Injection and monitoring system was placed to inject into and monitor changes within the upper aquitard. One well was used for groundwater extraction, substrate injection, and process monitoring.	NA	Pilot test complete/ follow up unknown	Monthly for the first 3 months.	NA
Lauderick Creek Area of Concern, Main Plume, Aberdeen Proving Ground	MD	Pilot	Lactic Acid	NA	NA	Vitamin B12, yeast extract	NA	NA	NA	NA	Pilot test complete/ follow up unknown	2 process monitoring events 6-7 weeks apart.	NA
Lauderick Creek Area of Concern, Southern Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lauderick Creek Area of Concern, Southeast Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lauderick Creek Area of Concern, North Plume Area, Aberdeen Proving Ground	MD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Southern US Industrial Site	Unknown	Full	Lactate and Acetate	NA	NA	Ammonium Phosphate	150,000	25	36 dual extraction wells run on average approximately 60% of the time. Substrate is injected periodically through 7 injection wells.	March, 1998/ ongoing	Monitoring continues to date	Biannually through September 1999	NA
Molasses													
Avco Lycoming Superfund Site	Williamsport, PA	Pilot, Full	Molasses	NA	NA	None	Approximately 5,000	11	20 injection wells - flow rate controlled by PLC	November 1995 to June 1996 - Pilot January 1997 to July 1998 - Full	Ongoing	Quarterly	NA
Cedarburgh Drycleaners	Cedarburgh, WI	Full	Molasses	NA	NA	None	11,550	25 - 28'	Geoprobe, infiltration gallery	NA	NA	Semiannual	NA
Industrial Site	Central Ohio	Pilot	Molasses	NA	NA	Sodium Phosphate, ammonium Chloride, monopotassium phosphate	Phase 1: 500 Phase II: 4,500 Phase III: 32,000	25	Phase I consisted of 1 injection well, 1 injection well, and 1 monitoring well. Phase II consisted of 2 injection wells and 9 monitoring wells. Phase III used the same injection wells installed for Phase II but added 20 more monitoring wells.	November 1996 / 5 years	NA / NA	Monthly for 6 months	Phase I was designed to confirm the capability of enhancing reductive dechlorination in-situ. Phase II was designed to evaluate amendment distribution strategies. Phase II was designed to the maximum volume of aquifer that could be impacted by a single well injection. Contaminant concentration data were collected during Phase I only.
Washington Square Mall	Germantown, WI	Full	Molasses (47% carbohydrate during pilot; 66% during full)	NA	NA	None	30,000	5	Geoprobe, infiltration gallery	August '98; 6 months - Pilot March '99; 6 months - Full	Site closed	Quarterly	Site closure from WDNR, less than 2.5 yrs after initiating the in situ reaction zone

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Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description
Molasses (Continued)												
Manufacturing Facility	Greenville, SC	Yes	CT	Industrial	South Carolina Dept. Health & Environmental Control	Site closure	Pilot, Full	Pilot - March 1998 Full - October 2001	Elizabeth Rhine, ARCADIS 864-242-1717	Phase 1 ongoing, to be followed by Phase 2 which will treat leading edge of plume	Shetty and Liles, 1999; Horst *et al*., 2000 Pahr *et al.*, 2002	Silty sand and sandy silt (saprolite) overlying a highly weathered transition zone. Bedrock consists of mostly granitic gneiss and schist.
Crestwood Site	Glendale, WI	Yes	NA	Industrial	WDNR	Mass reduction, natural attenuation for low-level residuals	Full	1998	Michael Maierle, ARCADIS 414-276-7742	Ongoing	Horst *et al*., 2000	Approximately 4 to 12 feet of fill material overlying 4 to 8' of sand; clay till aquitard underlies the sand bed.
Emeryville Manufacturing Facility	Emeryville, CA	Yes	TCE, DCE	Industrial	SFRWQCB	Reduce average concentration of total chromium and TCE in groundwater by more than 90%	Pilot, Full	Pilot - August 1995 Full - April 1997	Chris Lutes, ARCADIS	Ongoing	Shetty and Liles, 1999; USEPA, 2000b; Horst *et al*., 2000; Nyer *et al*., 2000	Interbedded sand and clay to a depth of 24 feet underlain by impermeable clay
Manufacturing Facility	Northeastern USA	Yes	PCE	Industrial	NA	NA	Full	Pilot - October 1998 Full - April 2000	Frank Lenzo, ARCADIS	NA	Nyer *et al*., 2000 Payne *et al*., 2001	10-20' thick overburden of glacial sands, silts and clays; water table in underlying bedrock.
Reliant Corporation Site	Blairsville, GA	No	TCE,DCE	Industrial	EPD HSRA Branch	Reduce site concentrations below Type 4 RRS values and off site concentrations to below Type 2 RRS	Full	NA	Brian Lawrence	Ongoing	Arcadis, 2002	NA
Nuclear Fuel Services Site	Erwin, TN	Yes	PCE, TCE	DOE	NRC, TDEC-DSWM, EPA Region IV	Reduce VOC concentrations, contain plume migration	Pilot	August 2000	Janice Green (423) 743-1730 or Scott Morie (423) 743-9141	Full scale implementation is scheduled for 2nd quarter, 2002	Arcadis, 2002 Morie *et al*., 2002	0-30' Alluvial silts, clays, clayey sand, sand w/ gravel and cobbles underlain by weathered, fractured, steeply dipping shale interbedded with siltstone and dolomite bedrock
TRW Automotive	Rogersville, TN	Yes	PCE	Industrial	TDEC-DSF	Reduce VOC concentrations	Pilot	NA	Dean Glenn (423) 272-4298	Closure monitoring	NA	0-30' Alluvial silts, clays, clayey sand, sand w/ gravel and cobbles underlain by weathered, fractured bedrock
Hanscom AFB	Bedford, MA	Yes	TCE, DCE, VC	Air Force	NA	Technology demonstration	Pilot	October 2000	Chris Lutes, ARCADIS	Ongoing	Liles, D. S., 2002	Upper and lower aquifers consisting of glacial till overburden overlying bedrock and separated by a stiff, laminated glaciolacustrine silt with clay
Vandenberg AFB	Lompoc, CA	Yes	TCE	Air Force	NA	Technology demonstration	Pilot	February 2001	Chris Lutes, ARCADIS	Ongoing	NA	Alluvial marine sands (with gravel, silt, and clay) over siltstone
Ohio Industrial Site	Southwestern Ohio	Yes	PCE, TCE	Industrial	State of Ohio	Plume restoration by reactive barrier	Full	1999	Chris Lutes, ARCADIS	Ongoing remediation	Payne *et al*., 2001	Porous, high carbonate aquifer

Site Name (Sorted by Substrate)	Site Location	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Molasses (Continued)													
Manufacturing Facility	Greenville, SC	375	22 - 34'	All zones	saprolite: 0.622 transition: 1.44 bedrock: 0.728	-0.63	saprolite: 0.3 bedrock: 0.05	saprolite: 30 bedrock: 200	Manufacturing facility	CT = 0.19 - 1.2	Target: 0.005	Chloroform, TCE, PCE, other VOCs	NA
Crestwood Site	Glendale, WI	NA	6 to 10	Unconfined aquifer	NA	NA	NA	37 to 110	Former drycleaning facility	PCE - 44.0	NA	NA	NA
Emeryville Manufacturing Facility	Emeryville, CA	NA	3.5 - 8'	Unconfined aquifer	NA	NA	NA	60	Metal plating and degreasing operations	PCE - 0.084 TCE - 6.5 DCE - 0.590 VC - 0.010	PCE - < 0.005 TCE - < 0.005 DCE - < 0.005 VC - 0.021	Hexavalent chromium	NA
Manufacturing Facility	Northeastern USA	NA	25 - 30'	Bedrock aquifer	0.14 to 1.78	NA	NA	10 - 70	Manufacturing facility	PCE - 80 TCE - 1 DCE - 1 VC - ND Ethene - < 0.001	PCE - 0.001 TCE - 0.001 DCE - 0.001 VC - 0.002 Ethene - 1.4 mg/l	NA	NA
Reliant Corporation Site	Blairsville, GA	NA	25	NA	0.015	NA	NA	NA	Former hot-mix asphalt manufacturing plant	TCE - 0.18 DCE - 0.23 VC - ND Ethene - 0.602	TCE - 0.131 DCE - VC - ND Ethene - ND	NA	NA
Nuclear Fuel Services Site	Erwin, TN	NA	4	Unconfined aquifer	0.18	NA	NA	62	Uranium fuel production facility	PCE - 12.4 TCE - 1.14 DCE - 0.66 VC - 0.13 Ethene - 0.024	PCE - 0.85 TCE - 0.32 DCE - 67.8 VC - 13 Ethene - 1.6	Uranium	Within 6 months following substrate injection PCE, and DCE contaminant mass had been reduced by 93% and 82% respectively. Within the same time period DCE, VC, and ethene concentrations increased by approximately 2 orders of magnitude.
TRW Automotive	Rogersville, TN	NA	22	Unconfined aquifer	0.0017	NA	NA	0.62	Automotive parts manufacturing	PCE - 22 TCE - 0.005 DCE - 0.042 VC - 0.001 Ethene - 0.009	PCE - 0.0022 TCE - < 0.002 DCE - 0.0086 VC - 0.0226 Ethene - 0.024	NA	NA
Hanscom AFB	Bedford, MA	<529 to 1900	4 to 8	Study focuses on lower, confined aquifer	26	0.006	NA	292	Pyrokinetic training and research	TCE - 1.9 DCE - 5.3 VC - 1.3 Ethene - 0.17	TCE - 1.9 DCE - 5.3 VC - 1.3 Ethene - 0.17	1,1-DCA, 1,1-DCE	Post-treatment concentrations are those from existing monitoring well after 19 months of demonstration testing
Vandenberg AFB	Lompoc, CA	<648	13'	Unconfined sand aquifer	1	0.041	NA	40 - 168	Missile silo	TCE - 4.0	TCE - 0.019	NA	Concentrations from existing monitoring well showing good treatment.
Ohio Industrial Site	Southwestern Ohio	NA	NA	Unconfined, high carbonate aquifer	NA	NA	NA	360	NA	PCE - 0.5 TCE - 0.7 VC - 0.003 Ethene - <0.001	PCE - <0.001 TCE - <0.001 VC - <0.001 Ethene - <0.001	NA	Within approximately 440 days following substrate injection PCE, TCE, DCE, and VC concentrations in groundwater had been reduced by nearly 100%. At day 180 DCE concentrations peaked and began to decline while ethene concentrations peaked at day 240.

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Total Organic Carbon Maximum Pre-Treatment (mg/L)	Total Organic Carbon Maximum Post-Treatment (mg/L)	Dissolved Oxygen Range Pre-Treatment (mg/L)	Dissolved Oxygen Range Post-Treatment (mg/L)	ORP Range Pre-Treatment (mV)	ORP Range Post-Treatment (mV)	pH Range Pre-Treatment (su)	pH Range Post-Treatment (su)	Nitrate Range Pre-Treatment (mg/L)	Nitrate Range Post-Treatment (mg/L)	Ferrous Iron Range Pre-Treatment (mg/L)	Ferrous Iron Range Post-Treatment (mg/L)	Sulfate Range Pre-Treatment (mg/L)	Sulfate Range Post-Treatment (mg/L)	Methane Range Pre-Treatment (mg/L)	Methane Range Post-Treatment (mg/L)
Molasses (Continued)																	
Manufacturing Facility	Greenville, SC	6.3	NA	0.95 - 3.22	NA	64 - 246	-50 average	3.8 - 5.6	NA	ND - 0.1	NA	ND - 1.8	NA	ND - 12.5 (av. 3.1)	NA	NA	NA
Crestwood Site	Glendale, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Emeryville Manufacturing Facility	Emeryville, CA	NM	NM	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	Northeastern USA	2	469 (MW) >3000 (inj)	NA	NA	NA	NA	7	3.7	NA	NA	NA	NA	NA	NA	NA	NA
Reliant Corporation Site	Blairsville, GA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nuclear Fuel Services Site	Erwin, TN	5	31	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
TRW Automotive	Rogersville, TN	2	9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hanscom AFB	Bedford, MA	6.2	525	0.35 - 1.48	0 - 0.7	-57.5 to +200	-167 to -44	5.7 - 7.1	5.9 to 7.1	ND	ND - 0.27	0.15 - 12.3	ND to 142	21.5 - 38.9	0.22 - 30.1	15 - 139	23 - 2255
Vandenberg AFB	Lompoc, CA	4.8	4260	1.68 - 4.8	0 - 2.5	+337 to +439	-301 to +188	6.2 - 6.7	4.1 - 6.1	4.7 - 11.3	ND - 11.7	ND - 0.038	ND - 135	183 - 306	6.5 - 418	ND - 6	ND - 7608
Ohio Industrial Site	Southwestern Ohio	NA	NA	NA	NA	NA	NA	6.9	5.5	NA	NA	NA	NA	NA	NA	NA	NA

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area Surface Area (sq. ft)	Treatment Area Thickness (feet)	System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
Molasses (Continued)													
Manufacturing Facility	Greenville, SC	Full Scale	Molasses	$1.25/gal.	$30,000/yr.	None	170,000	25 - 73	Fully automated	2 years		Monthly for TOC Quarterly for VOCs	NA
Crestwood Site	Glendale, WI	Full	Molasses	NA	NA	NA	NA	NA	Geoprobe, infiltration gallery	NA	NA	NA	NA
Emeryville Manufacturing Facility	Emeryville, CA	Pilot, Full	Molasses	$3.00 per gallon	NA	Anaerobic digester sludge	NA	NA	91 injection pts with Geoprobe	NA	NA	NA	Closure, all contaminant concentrations were below MCLs.
Manufacturing Facility	Northeastern USA	Full	Molasses, 200 gal; 10% carbohydrates in each well	$0.30	$5,000/year	none (Zero valent iron proposed for source area 2002.)	450,000	50-190	Batch delivery under pressure to 11 injection wells	2 to 5 years of injections	Ongoing	Quarterly	Full-scale containment in place in mid-plume 2000 to 2002. Full scale source area injection program began in October 2001.
Reliant Corporation Site	Blairsville, GA	Full	Molasses	$0.12	NA	Bioaugmentation using anaerobic microbes from a anaerobic wastewater treatment facility utilized approximately 1% by volume of injected substrate on two occasions.	NA	NA	currently 32 injection wells - either gravity feed or using centrifugal pump bimonthly injection	NA	NA	NA	NA
Nuclear Fuel Services Site	Erwin, TN	Pilot	Molasses; 363 gallons	$0.15	NA	None	NA	NA	NA	8 months	NA	NA	The pilot scale application was considered a success and full scale applications are scheduled for "designated source areas" in the 2nd quarter of 2002.
TRW Automotive	Rogersville, TN	Pilot	Molasses; 220 gallons	$0.15	NA	None	NA	NA	NA	4 months	NA	NA	Closure monitoring ongoing.
Hanscom AFB	Bedford, MA	Pilot	Molasses: roughly 20 gallons every two weeks	NA	NA	None	~5000	50	One injection well. Manual, pressurized injections. Post-injection water pushes.	June 2000; ongoing	Ongoing	About monthly for process parameters. About quarterly for COCs, dissolved gasses, etc.	AFCEE/ESTCP Demonstration.
Vandenberg AFB	Lompoc, CA	Pilot	Molasses: variable frequency and amount based on injection well process monitoring data.	NA	NA	None	~1000	30	Three injection wells. Manual, pressurized injections.	April 2001; ongoing	Ongoing	About monthly for process parameters. About quarterly for COCs, dissolved. gasses, etc.	AFCEE/ESTCP Demonstration.
Ohio Industrial Site	Southwestern Ohio	Full	5 to 10 percent molasses solution biweekly for 6 months, intermittent thereafter	NA	NA	None	NA	NA	Reactive barrier configuration	Ongoing for over two years	Ongoing	Every 3-4 months on average	NA

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description
Molasses (Continued)												
Manufacturing Facility	Southeast England	Yes	TCE	Industrial	NA	Plume restoration, partially underneath the facility	Full	1999	Chris Lutes, ARCADIS	Ongoing remediation	Arcadis, 2002	Sandy gravel alluvium overlying a thick regional aquitard known as the London Clay
Former Manufacturing Facility	North Carolina	Yes	PCE, TCE	Industrial	NA	Technology Demonstration	Pilot	2001	Nanjun Shetty and William Doucette, Jr., ENSR Corporation, NC	Pilot test process monitoring is ongoing	Shetty and Doucette, 2002	Silty clay
KAP Incorporated Manufacturing Facility	Czech Republic	No	PCE	Industrial	NA	Technology Demonstration	Pilot	July 2000	Jirina Machackova, KAP Limited, Czech Republic	Process monitoring is ongoing	Soukup *et al*., 2002	NA
Chemical Manufacturing Facility	Eastern PA	No	TCE, DCE, VC, Nickel	Industrial	PA DEP	Improve groundwater quality sufficiently so that a groundwater pump and treat system could be shut down	Full	NA	Kurt Beil, Arcadis	NA	Beil *et al*., 2002	NA
Shopping Center Redevelopment	Santa Barbara, CA	No	PCE	Industrial	California RWQCB	Groundwater cleanup for site closure	Full	NA	Chris Lutes, ARCADIS	Site closed based on meeting negotiated groundwater cleanu standards equal to VOC concentrations in an upgradient well.	Arcadis, 2002	NA
Butyrate												
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	Yes	TCE, DCE, VC	Navy	USEPA	Treatability study	Microcosms, Pilot	June 1999	Bruce Alleman, Battelle Jeff Morse, Battelle	Demonstration Completed	NATO, 2000; AFRL *et al.* , 2001	NA
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	Yes	TCE, DCE	Army	NA	Treatability study	Microcosms, Pilot	August 2000	Jeff Morse, Battelle	Demonstration Completed	AFRL *et al.* , 2001	NA
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	Yes	PCE, TCE	Marine Corps	NA	Treatability study	Microcosms, Pilot	June 2001	Jeff Morse, Battelle	Demonstration Completed	AFRL *et al.* , 2001	Sand and clay sediments to 75 ft bgs. A series of sand and limestone beds occur between 50 and 300 ft bgs, associated with the Castle Hayne Aquifer (CHA).
Acetate												
Hanford 200 Area Site	Richland, WA	Yes	CT, Nitrate	DOE	NA	Technology demonstration	Pilot	January 1995 to March 1996	Rod Skeen, Pacific Northwest National Laboratory 509-375-2265	Demonstration Completed	DOE, 1999	Unsaturated zone extends to a depth of 250 feet. Two permeable zones are located at 250 to 256 feet bgs and 285 to 302 feet bgs with a competant aquitard between.
Gillette Company Site	Eastern US	Yes	TCE	Industrial	MA DEP	Technology demonstration	Pilot	NA	Paula Chang, Geosyntec	NA	Chang *et al.* , 2002	NA
Manufacturing Facility	NJ	Yes	PCE, TCE	Industrial	NA	Technology demonstration	Pilot	1998	David Lipson, BBL	NA	Lipson, D. S., and Persico, J. L., 2002	Thin saturated soil over fractured basaltic bedrock

Site Name (Sorted by Substrate)	Site Location	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Molasses (Continued)													
Manufacturing Facility	Southeast England	NA	20	Unconfined sandy gravel aquifer	260	NA	NA	1000	Manufacturing facility	TCE - 22 DCE - 12 VC - 0.045 Ethene - 0.002	TCE - 0.014 DCE - 20.8 VC - 4.5 Ethene - 1.1	Petroleum constituents	Since substrate injection in 1999 the average TCE concentration has decreased by nearly 100% while VC and ethane concentrations have increased by 1 and three orders of magnitude respectively and the average DCE concentration has increased by approximately 73%.
Former Manufacturing Facility	North Carolina	NA	NA	Unconfined silty clay aquifer	NA	NA	NA	2.6 - 11.2	Manufacturing facility	PCE - 11 TCE - 0.18	NA	NA	NA
KAP Incorporated Manufacturing Facility	Czech Republic	NA	NA	NA	NA	NA	NA	NA	Manufacturing facility	TCE - 20 DCE - NA VC - NA Ethene - NA	TCE - 0.5 DCE - 0.5 VC - 0.2 Ethene - NA	NA	Approximately 17 months after the start of substrate addition the cleanup goals of 0.5 mg/L TCE and DCE and 0.2 mg/L VC were met indicating that TCE mas was reduced by approximately 98%. Baseline DCE and VC data were not provided.
Chemical Manufacturing Facility	Eastern PA	NA	NA	NA	NA	NA	NA	NA	Chemical manufacturing plant	NA	NA	NA	NA
Shopping Center Redevelopment	Santa Barbara, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Site was closed when VOC concentrations were reduced to levels at or below concentrations coming in from an offsite source.
Butyrate													
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	NA	4.4 to 6.5	Unconfined shallow with low groundwater velocity	0.006 to 0.019	NA	NA	11.4	Former engine testing and repair facility	TCE - 24 DCE - 8.6 VC - 2.2 Ethene - NA	TCE - 0.7 DCE - 2.4 VC - 0.6 Ethene - 2.0	Dichlorobenzene, methylene chloride, toluene, sodium hydroxide	Water injected with amendments contained average TCE, cDCE, and VC concentrations of 81.7 mM, 7.0 mM, and 3.4 mM, respectively. Average TCE concentrations were reduced by 94% by the end of the demonstration.
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	NA	10	Unconfined	NA	NA	NA	91 to 274	Waste Storage and Disposal Area	TCE - 1.5 to 6.3	TCE - 0.069 DCE - NA VC - 0.217	BTEX	Injected TCE concentrations spiked as high as 169 mg/L, but this did not prove toxic to the microorganisms.
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	NA	NA	Unconfined surficial aquifer up to about 50 ft bgs. Receptors include the CHA, which is the principal water supply for the base.	0.4 - 30	NA	NA	NA	Drycleaning operations, leaking underground storage tanks	NA	Average instead of max: PCE - 5.5 TCE - 0.4 DCE - 0.08 VC - < 0.006	NA	NA
Acetate													
Hanford 200 Area Site	Richland, WA	NA	250	Unconfined high permeability aquifer perched by a 30 aquitard. Confined aquifer lies beneath the aquitard and extends to approximately 302 feet bgs.	high	NA	NA	NA	Sanitary tile disposal site for the 221-T plant	CT - Nitrate -	CT - Nitrate -	NA	Approximately 2 kg of CT was reported to have been destroyed during the 14 month pilot test. Within the same time period approximately 30 kilograms (dry weight) of bacterial biomass was produced.
Gillette Company Site	Eastern US	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	NJ	NA	NA	unconfined overburden aquifer over a fractured bedrock aquifer.	NA	NA	NA	NA	Manufacturing facility	NA	NA	NA	NA

APPENDIX B - ENHANCED BIOREMEDIATION DATABASE

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanc

		Total Organic Carbon		Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane	
Site Name (Sorted by Substrate)	Site Location	Maximum Pre-Treatment (mg/L)	Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)
Molasses (Continued)																	
Manufacturing Facility	Southeast England	14.5	11	3.68 - 4.8	0.02 - 0.32	+37 - +39	-113 - -178	6.63 - 6.81	6.95 - 7.1	0.6 - 0.7	<0.3 - 0.9	<0.1 - 9.0	5.33	160 - 210	33 - 124	0.078 - 0.143	0.03 - 3.3
Former Manufacturing Facility	North Carolina	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
KAP Incorporated Manufacturing Facility	Czech Republic	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Chemical Manufacturing Facility	Eastern PA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Shopping Center Redevelopment	Santa Barbara, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Butyrate																	
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	120	NA	< 1	NA	NA	Approximately - 200	7.0 to 7.8	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Acetate																	
Hanford 200 Area Site	Richland, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Gillette Company Site	Eastern US	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Manufacturing Facility	NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area: Surface Area (sq. ft)	Treatment Area: Thickness (feet)	System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
Molasses (Continued)													
Manufacturing Facility	Southeast England	Full	Molasses, 35,805 lb through September 2002	$0.20	$7,161	None	NA	NA	A total of 53 injection wells wer installed under the future site of a new building. Each injection well was piped separately to the injection system installed in a separate building so that substrate injection could be controlled by well. 7 monitoring wells were installed up and down gradient from the injection area. During the first two years 15,000 lb were injected at a rate of 21 lb/day. In 9/01 the feed rate was increased to 57 lb/day. Injection was ongoing at the increased rate through spring 2002.	June 1999 / NA	Substrate injection and process monitoring are ongoing	Quarterly	During the life cycle of this application substrate injection rates have been very carefully monitored and controlled in order to control the rate of reductive dechlorination. The rate of reductive dechlorination had to be strictly controlled so that DCE and VC did not accumulate and intrude in to the building constructed above the injection area.
Former Manufacturing Facility	North Carolina	Pilot	NA	NA	NA	NA	NA	NA	NA	NA / 1 year	Ongoing	quarterly	PCE and TCE concentration decreases of 89% and 94% respectively, were reported although analytical data was not provided.
KAP Incorporated Manufacturing Facility	Czech Republic	Pilot	Molasses, NA	NA	NA	None	35,000	NA	NA	NA	NA	NA	NA
Chemical Manufacturing Facility	Eastern PA	NA	Molasses, NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Shopping Center Redevelopment	Santa Barbara, CA	Full	Molasses, NA	NA	NA	NA	NA	NA	NA	NA	Site closed in May 2000	None	Site was closed when VOC concentrations were reduced to levels at or below concentrations coming in from an offsite source.
Butyrate													
Naval Air Station Alameda Building 360 (Site #4)	Alameda, CA	Microcosms, Pilot	Butyric acid (3mM) at 236 gal/day (0.62 L/min)	NA	NA	Yeast extract, 20 mg/L	45	3	Single injection well, single extraction well, and nine monitoring points at depths of 24 to 27 feet bgs	194 days	Demonstration Complete	Biweekly	On average, 87% of injected chloroethenes could be accounted for, with ethene levels accounting for approximately 50% of the total chloroethene concentration.
Fort Lewis East Gate Disposal Yard	Fort Lewis, WA	Microcosms, Pilot	Butyric acid; 1.5 L/min	NA	NA	Yeast extract, 20 mg/L; Sodium bicarbonate, 279 mg/L	120	3	Three injection wells spaced 2 ft apart; system of monitoring wells; existing well in zone of contamination used to supply injection water for test plot	179 days	Demonstration Complete	Biweekly	Calculated TCE half lives of 4.4 to 4.7 hours. cDCE accumulated with VC comprising a small percentage of overall mass. Ethene and ethane remained at or below detection.
Marine Corps Camp Lejeune Site 88	Camp Lejeune, NC	Microcosms, Pilot	Butyric acid; 0.65 L/min	NA	NA	Yeast extract, 20 mg/L	120	3	Three injection wells, nine monitoring wells at depths of 45 to 48 feet bgs.	180 days	Demonstration Complete	Biweekly	NA
Acetate													
Hanford 200 Area Site	Richland, WA	Pilot	Acetate	NA	NA	Nitrate	400	10	One injection well and one extraction well were installed and run continuously as a recirculation system two monitoring wells were installed between the injection and extraction wells for process monitoring.	January 1995/ 14 months	Pilot Test Complete	NA	Acetate and nitrate were injected and recirculated through 2 aquifer zones to treat carbon tetrachloride and nitrate contamination. Approximatley 30 kg (dry weight) of bacterial biomass was produced and approximately 2 kg of CT was broken down during the course of the 14 month pilot study.
Gillette Company Site	Eastern US	NA	Acetate	NA	NA	Methanol and microbial amendment KB-1	NA	NA	One injection well and one extraction well were installed. Acetate was injected to reduce sulfate mass and to push geochemistry to more reducing conditions. 3 months after acetate injection, bioaugmentation with methanol and KB-1 was performed.	NA/NA	NA/NA	NA	This site had high sulfate (>1000 mg/L), high salinity, and tidal impact due to close proximity of the coast. The target zone was also deep >100 ft. TCE degradation to DCE was noted early on but DCE degradation and VC/ethene accumulation was not observed until 4 months after bioaugmentation with the KB-1 commercial bioaugmentation product.
Manufacturing Facility	NJ	Pilot	Acetate, 1000 lb	NA	NA	NA	NA	NA	NA	NA	NA/NA	NA	Acetate injection into a surficial overburden aquifer/fractured bedrock aquifer.

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description
Methanol and Acetate												
Building 360, Kelly Air Force Base	South Central TX	Yes	PCE, TCE, DCE	Air Force	TNRCC	Technology demonstration/ source reduction	Bench, Pilot	December, 1999	David Major, Geosyntec	NA	Newell *et al*., 2002; Major *et al*., 2001	20 to 40 feet of alluvial gravel, sand, and silt overlying impermeable clay.
Rademarkt Site	Groningen, Netherlands	Yes	PCE, TCE, DCE, VC	Industrial	NA	Technology Demonstration	Pilot	NA	NA	NA	Langenhoff *et al*., 2001	NA
Lactose, Fructose												
Former Municipal Waste Water Treatment Facility (Lactose)	NH	Yes	PCE, TCE, TCA	Industrial	New Hampshire DES	Groundwater remediation to potable water standards	Full	Pilot: 1997 Full: 2000	Richard Schaffner, Jr., GZA Environmental	Full scale in progress (scheduled until 2003)	Schaffer *et al*., 2001	Upper fine sand and silt unit (5-20'); Lower sandy and silt unit (30-50' bgs); aquitard generally extends from 20 to 30 feet bgs
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	Yes	TCE	Navy	Tennessee DEC, USEPA	Feasibility test for groundwater restoration	Pilot	March 2000	Ronnie Britto, Ensafe, Inc.	Pilot test complete with continued monitoring, Currently preparing CMS	Britto *et al.*, 2002	Fluvial deposits aquifer
Sodium Benzoate												
New England Super Fund Site	New England	Yes	DCE, Tetrahydrofuran, Fuel Hydrocarbons	Industrial	NA	Technology demonstration for enhanced bioremediation as a cost effective alternative to pump and treat	Pilot	January 1998	Craig Lozolte, Envirogen Inc.	NA	Turpie *et al*., 2000	NA
Ethanol												
Sages Drycleaner	Jacksonville, FL	Yes	PCE DNAPL	Industrial	Florida DEP	Technology Demonstration to remove PCE DNAPL	Pilot	June 1998	James Jawitz, University of Florida, Gainesville	Pilot test completed / NA	Jawitz *et al*., 2000	Approximately 30 feet of fine sand underlain by approximately 6 feet of silty sand
Hydrogen Release Compound (HRC)												
Contemporary Cleaners	Orlando, FL	Yes	PCE, TCE, DCE, VC	Industrial	Florida DEP	Groundwater remediation via accelerated anaerobic biodegradation	Full	36161	Mike Ladato, IT Corp. 813-626-2336	Ongoing	State Coalition for Remediation of Drycleaners (Orlando, FL); Kean *et al*., 2000, Lodato *et al*., 2000; Kean *et al.*, 2002; Regenesis Case History #H 1.4 and 1.8	Fine grained quartz sand (25-30'), clay 1-12'; fine grained sand and sandy clay 20-25'
Decorah Shopping Center Drycleaners	Decorah, WI	Yes	PCE	Industrial	Wisconsin DNR	Contaminant source removal, plume stabilization, groundwater restoration	Full	1999	Curtis M. Hoffart Key Engineering 414-375-4750	Ongoing	State Coalition for Remediation of Drycleaners (Decorah, WI)	Sandy silt and silty sand with varying amounts of clay (5'), med grained sand (5'-11'bgs) silty sand and sandy silt with silty clay (11-24'bgs), silty clay (24-28'bgs)
Dixie Cleaners	Jacksonville, FL	Yes	PCE, TCE, DCE, VC	Industrial	Florida DEP	Source zone remediation	Pilot	36617	Willard Murray, Rao Angara, Harding ESE 781-245-6606	Ongoing, Scale-up to Full Scale	State Coalition for Remediation of Drycleaners (Jacksonville, FL); Murray *et al.*, 2001, Watts *et al*., 2002	Silty , fine-grained sand (0-18' bgs); clayey fine-grained sand (18-30' bgs); limestone (30-32' bgs)
Dover Park Plaza Drycleaning Facility	Yardville, NJ	Yes	PCE, DCE	Industrial	NJDEP	Source zone and plume remediation	Pilot, Full	36312	Robert North, ENVIRON International 609-243-9854	Performance monitoring	Koenigsberg *et al*., 2000; North *et al.*, 2001	Shallow sand (15-22'), dense silty clay (30')

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Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Methanol and Acetate													
Building 360, Kelly Air Force Base	South Central TX	NA	5 to 10	Unconfined aquifer at 5 to 10 feet bgs	NA	NA	NA	1095	Aircraft maintenance and cleaning	PCE - 8.1 TCE - 0.19 DCE - 2.1 VC - ND Ethene - ND	PCE - 0.81 (est.) TCE - 0.019 (est.) DCE - 0.315 (est.) VC -NA Ethene - NA	None	Reported a 90% reduction in PCE. Cis-1,2-DCE degradation was observed only after the addition of the KB-1 microbial consirtium amendment.
Rademarkt Site	Groningen, Netherlands	NA	NA	NA	NA	NA	NA	NA	NA	PCE - 1.28 TCE - 1.03 DCE - 2.6 VC - 0.94 Ethene - NA	PCE - 0.60 TCE - 0.01 DCE - 0.29 VC - 2.26 Ethene - NA	NA	Contaminant concentration reductions represent site average concentrations before injection and 25 weeks after injection.
Lactose, Fructose													
Former Municipal Waste Water Treatment Facility (Lactose)	NH	NA	5 to 10	Shallow unconfined upper hydrogeologic unit with a semi-confined lower hydrogeologic unit	0.28 to 2.8	0.001	NA	NA	Sludge disposal pit	PCE - 0.02 TCE - 0.3 DCE - 8.4 VC - 1.5 Ethene - N/A	PCE - < 0.001 TCE - < 0.001 DCE - 2.7 VC - 0.3 Ethene - N/A	NA	NA
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	<25	47 - 79	Unconfined to semi-confined aquifer 80 to 100 feet thick	44 to 68	0.004	27 (est.)	45 (upper) 22 (lower)	Aircraft Maintenance Operations	NA	NA	NA	NA
Sodium Benzoate													
New England Super Fund Site	New England	NA	NA	NA	NA	NA	NA	NA	Landfill	NA	NA	Arsenic	Degradation rates were calculated for *cis*-1,2-DCE and VC based on production rates of ethene and ethane for the first two years of operation. The average half life calculated for *cis*-1,2-DCE was 255 days. The calculated average half life for VC was 48 days.
Ethanol													
Sages Drycleaner	Jacksonville, FL	NA	9	Shallow, unconfined, sandy aquifer	20 - upper sand unit 10 - lower silty sand unit	0.0025	NA	NA	Drycleaning facility	PCE - 150	PCE - 44	NA	Approximately 43 liters of PCE were recovered from the extracted water/ethanol waste stream. This PCE mass represents approximately 63% of the total PCE mass present in the flushed area indicating that the extraction efficiency is 63%.
Hydrogen Release Compound (HRC)													
Contemporary Cleaners	Orlando, FL	NA	6 - 8	Unconfined upper surficial aquifer underlain by a thin aquitard and a confined lower surficial aquifer	1.3 (upper) 65 (lower)	0.01 (upper) 0.003 (lower)	NA	16 (upper) 2.6 (lower)	Drycleaning facility	PCE - 19.2 TCE - 2.5 DCE - 6.3 VC - 2.4	PCE - 0.82 TCE - 1.3 DCE - 4.0 VC - 1.0	NA	Within 152 days following injection PCE, TCE, DCE, and VC concentrations were reduced by 96%, 48%, 38%, and 58%, respectively, over 5 wells screened in the shallow aquifer.
Decorah Shopping Center Drycleaners	Decorah, WI	NA	6 - 10	NA	3.7	0.028	NA	NA	Drycleaning facility	PCE - 0.018 TCE - 0.0004 DCE - < 0.001	NA	NA	This project has not been implemented as of spring 2002
Dixie Cleaners	Jacksonville, FL	NA	2	Unconfined aquifer	0.31(shallow sand); 0.23 (clayey sand)	NA	NA	0.00279 (shallow sand) 0.00207 (clay)	Drycleaning facility	PCE - 5.2 TCE - 12.7 DCE - 7.5 VC - 1.1	PCE - 0.042 TCE - 1.3 DCE - < 0.005 VC - N/A	NA	Average PCE, TCE, and DCE concentrations were reduced by 99%, 90%, and 99% 7 months after injection.
Dover Park Plaza Drycleaning Facility	Yardville, NJ	NA	10	Shallow unconfined aquifer.	14.2	0.007	NA	NA	Drycleaning facility	PCE - 1.4 TCE - 0.02 DCE - 0.1 VC - < 0.005 Ethene - < 0.005	PCE - < 0.005 TCE - < 0.005 DCE - 0.22 VC - < 0.005 Ethene - < 0.005	NA	After approximately 400 days following the full scale application PCE and TCE concentrations were reduced by approximately 99% and 75% respectively in one monitoring well. During the same time period DCE concentrations increased by approximately 120% in the same well.

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Summary of Information on Sites Implementing Enhanc

		Total Organic Carbon		Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane	
Site Name (Sorted by Substrate)	Site Location	Maximum Pre-Treatment (mg/L)	Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)
Methanol and Acetate																	
Building 360, Kelly Air Force Base	South Central TX	NA	NA	Approx. 2	NA	Aerobic conditions with small anaerobic pockets and zones	NA	NA	NA	Approx. 24	NA	Approx. 0.06	NA	Approx. 16	NA	ND	NA
Rademarkt Site	Groningen, Netherlands	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lactose, Fructose																	
Former Municipal Waste Water Treatment Facility (Lactose)	NH	0 - 10 mg/L (COD)	~ 10,000 mg/L (COD)	0.2 to 7.4	0 - 1.8	-55 to +310	-290 to +10	6.5-7.8	6.5-7.8	< 3.6	<0.05	NA	NA	20-35	<10	< 5	< 10
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sodium Benzoate																	
New England Super Fund Site	New England	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ethanol																	
Sages Drycleaner	Jacksonville, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hydrogen Release Compound (HRC)																	
Contemporary Cleaners	Orlando, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Decorah Shopping Center Drycleaners	Decorah, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dixie Cleaners	Jacksonville, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dover Park Plaza Drycleaning Facility	Yardville, NJ	1	720	2.4 - 5.3	0.3 - 0.7	+106 to +287	-146 to +37	4.5 - 6.1	4.1 - 6.5	NA	NA	ND - 5.0	3.8 - 5.6	36 - 67	2 - 67	< 0.007	< 1.44

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Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Thickness (feet)					
Methanol and Acetate													
Building 360, Kelly Air Force Base	South Central TX	Bench and Pilot	Methanol and Acetate	NA	NA	Bromide, KB-1 ("A naturally occurring microbial consortia isolated by GeoSyntec and Univ. of Toronto")	90	25	Closed loop circulation system consisting of 3 extraction wells, 1 injection well and 5 monitoring wells	December, 1999 / 320 days	Pilot Test Complete	Variable	DCE degradation was not observed until after the KB-1 microbial consortium was added.
Rademarkt Site	Groningen, Netherlands	Pilot	0.35% methanol, 1.44% compost leachate, 0.9 g/L ammonium chloride	NA	NA	ammonium chloride, sodium bromide	5,000	10	10 Injection wells were installed upgradient of 5 extraction wells. Groundwater was extracted, amended, and reinjected.	NA / 35 weeks	Pilot test was completed	NA	This application used methanol and compost leachate as a substrate to augment reductive dechlorination already occuring at the site.
Lactose, Fructose													
Former Municipal Waste Water Treatment Facility (Lactose)	NH	Full	Lactose (approx. 70%) and Yeast Extract (approx. 30%) (proprietary blend)	$0.22	$27,775	Proprietary mixture of lactose and yeast extract	~3.5 acres	150 feet bgs	Injection of blend pumped into 3 locations: 5,050 lbs biostimulant per 65,950 gallons injected during pilot; 22,100 lbs per 375 gallons injected during full-scale	1997-2000 - pilot 2000-2003 - full-scale 2003-pursue closure with MNA	Full scale in progress (scheduled until 2003)	Tri-annual	Monitoring program specified contaminants of concern DO, ORP, and COD. If COD concentrations exceed 25mg/L, then no other indicator parameters (e.g., nitrate, sulfate, methane, etc.) were deemed required.
Naval Support Activity Mid-South (Fructose, Acetate)	Millington, TN	Pilot	Fructose	NA	NA	Acetate	NA	NA	Recirculation system with one downgradient extraction well.	March 2000	Pilot test complete with continued monitoring, Currently preparing CMS	NA	NA
Sodium Benzoate													
New England Super Fund Site	New England	Pilot	Sodium Benzoate, injected as a 4 mg/L solution at a rate of 5 liters per point per day. As of December 1999 2,147 lb of substrate had been injected.	NA	NA	NA	NA	NA	30 electron donor injection points installed in sets of three (three injection intervals) in a barrier configuration. I upgradient and 3 downgradient rows of monitoring wells are used for process monitoring.	January 1998, 2 years	NA	biweekly for 1998, monthly for 1999	NA
Ethanol													
Sages Drycleaner	Jacksonville, FL	Pilot	Ethanol 8,980 gallons injected as a 95% ethanol in water mixture.	NA	NA	methanol, n-hexanol, and 2-ethyl-1-hexanol as tracers	130	10	3 injection wells surrounded by 6 recovery wells. Ethanol was injected at a total of 15 liters per minute for three days. Groundwater was extracted at a rate of 30.4 liters per minute to ensure containment of injected fluids.	June 1998 / 1 year	NA / NA	NA	The PCE extraction efficiency for the ethanol flush was approximately 63%. Approximately 718 gallons (8% of the total volume) of ethanol and an unknown quantity of methanol (10% of the injected volume) were left in the subsurface after flush activities were complete. Process monitoring results were not provided.
Hydrogen Release Compound (HRC)													
Contemporary Cleaners	Orlando, FL	Full	HRC; 6,800-lbs was injected into the shallow aquifer 18 months later 6,810 pounds were injected into the deep aquifer	$6.00	$40,800 1st application $40,860 2nd application	None	14,600	15	144 injection points installed within the upper aquifer on a 10 foot grid spacing. Second injection consisted of 145 injection points on a 10 foot grid.	NA/1 year	NA	Monthly for the first 6 months	Two HRC applications were performed on this site. The first application was performed in the shallow aquifer. The second application was performed 18 months later in the deep aquifer because the first application did not appear to be affecting contaminant mass present in the deep aquifer.
Decorah Shopping Center Drycleaners	Decorah, WI	Full	HRC; 3,000 lbs (forecast)	NA	NA	None	7,875	NA	20 injection points	NA	NA	NA	NA
Dixie Cleaners	Jacksonville, FL	Pilot	HRC; total of 22,000 pounds	NA	$150,000	None	18,400	10	175 injection points installed on a 10 foot grid spacing. 30 monitoring wells, 10 installed within each aquifer zone.	June 2000; 1 year	Considering methanotrophic insitu system	Bimonthly for the first year, quarterly thereafter.	Groundwater results from pilot test showed a sharp decrease in the concentrations of PCE and TCE
Dover Park Plaza Drycleaning Facility	Yardville, NJ	Pilot and Full	Pilot - 210 lb HRC Full - 4,860 lb HRC	Pilot - $7.86 Full - $6.00	Pilot - $1,650 Full - $29,160	None	Pilot - 42 Full - 3,900	5	Pilot - 8 direct injection wells installed in a semicircle 2.5 feet from one monitoring well. A second monitoring well was installed 3 feet downgradient from the outside edge of the injection point circle. Full - 159 injection points installed in 3 grids and 1 barrier.	NA	NA	Pilot - 16, 48, and 72 days following injection Full - Monthly for the first 6 months, quarterly thereafter.	NA

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Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description
Hydrogen Release Compound (HRC) (Contintued)												
Former Industrial Filter Manufacturer	Rochester, NY	Yes	TCE	Industrial	NYSDEC	Polish source area after removal of 2-Phase extraction system	Full	August 1998	Susan Boyle, Haley and Aldrich Inc. 585-359-9000	Conditional Closure	Boyle, *et al.*, 2000; Case *et al.*, 2001	Relatively low permeability clayey silts
Former Landfill Site 7, Duluth International Airport	Duluth, MN	Yes	TCE	Industrial	Minnesota PCA	Determine potential for groundwater remediation via anaerobic biodegradation	Pilot	April 2000	Robin Semer, Montgomery Watson Hazra 312-831-3800	Ongoing monitoring, Full-scale	Semer and Banerjee, 2001	NA
Watertown Industrial Area	Watertown, MA	Yes	PCE, TCE	Industrial	Massachusetts DEP	Feasibility study for enhanced anaerobic biodegradation	Pilot	February 1998	Willard Murray, Harding ESE 781-245-6606	Pilot Completed	Dooley *et al.*, 2000 Murray *et al.*, 2000, Murray *et al.*, 2001	Approximately 13 feet of sand and gravel overlying approximately 7 feet of silty sand. The surficial material is underlain by an aquitard consisting of glacial till.
Former Manufacturing Site	Walled Lake, MI	Yes	DCE, VC	Industrial	Michigan DEQ	Feasibility study for enhanced anaerobic biodegradation	Pilot	January 1999	Willard Murray, Harding ESE 781-245-6606	Ongoing	Murray *et al.*, 2000, Murray *et al.*, 2001	Silty sand
Unocal Wichita	Wichita, KS	Yes	PCE	Industrial	Kansas DEP	Feasibility study for enhanced anaerobic biodegradation	Pilot	September 1999	Willard Murray, Harding ESE 781-245-6606	Ongoing	Murray *et al.*, 2000, Murray *et al*., 2001; Koenigsberg *et al*., 2001	Silt and clay
FMC Corporation Site	San Jose, CA	Yes	TCE	Industrial	California RWQCB	Accelerate groundwater restoration	Pilot/Full	June 1999/May 2000	Jeff Bensch, HSI Geotrans 916-853-1800	Ongoing	Zahiraleslamzadeh and Bensch, 2000	Silty clays (45-50'); gravelly sand (30-35')
Hayden Island Cleaners	Portland, OR	Yes	PCE	Industrial	Oregon DEQ	Accelerate groundwater restoration	Full	May 1999	David Anderson, OR DEQ 503-229-5428	Ongoing	State Coalition for Remediation of Drycleaners (Orlando, FL); Anderson *et al*., 2000	20-40 feet of silty sand
Naval Air Station Dallas	Dallas, TX	Yes	PCE, TCE	Navy	USEPA	Groundwater remediation	Pilot	July 2000	Thomas Simpkin, CH2M Hill	Performance monitoring	CH2M Hill Constructors, 2001	Fine-grained fill, alluvial sediments, weathered shale
Naval Air Warfare Center	Indianapolis, IN	Yes	TCE, DCE	Navy	EPA, IDEM	Groundwater remediation	Full	NA	Dan MacGregor, CH2M Hill	Ongoing	NA	NA
Vandalia Manufacturing Facility	Vandalia, IL	No	PCE	Industrial	USEPA	Feasibility study for enhanced anaerobic biodegradation	Pilot	December 1998	Thea Schumacher, Levine Fricke 714-444-0111	Ongoing	Schuhmacher *et al*., 2000	Silty sand to coarse sand (14-20'bgs) overlying a fine grained glacial till
Hurlburt Field	Tallahasse, FL	Yes	TCE, DCE	DoD	USEPA	Accelerate natural attenuation of groundwater to less than 5 years	Pilot	January 1999	Will Harms, URS 850-574-3197	Performance monitoring	Harms *et al*., 2000 Regenesis Case History #H 1.3	The intermediate aquifer consists of sand, silty sand, and discontinuous lenses of clay and is located from 40 to 50 feet below ground surface.
Industrial Site	NJ	Yes	PCE	Industrial	NA	NA	Pilot	NA	Steve Koenigsberg, Regenesis 949-366-8000	NA	Koenigsberg *et al*., 2000; Koenigsberg *et al.*, 2001	NA
Drycleaning Facility	FL	No	PCE, TCE	Industrial	NA	NA	Full	NA	NA	NA	Murray *et al.*, 2001	NA

Site Name (Sorted by Substrate)	Site Location	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Hydrogen Release Compound (HRC) (Contintued)													
Former Industrial Filter Manufacturer	Rochester, NY	NA	1 to 2	Unconfined clayey silt aquifer	0.0003 to 0.003	NA	NA	NA	NA	TCE - 26 DCE - 0.34 VC - ND Ethene - ND	TCE - 4.7 DCE - 18 VC - 0.19 Ethene - 0.0731	None	Contaminant concentration data used to calculate mass reduction represents maximum values detected in 5 monitoring wells. Within 15 months of injection TCE concentrations were reduced by approximately 64% while DCE and VC concentrations increased by approximately 288% and 3700% respectively.
Former Landfill Site 7, Duluth International Airport	Duluth, MN	NA	5 - 6	Receptor one mile from site	NA	NA	NA	18 (surficial aquifer)	USAF Landfill active from the 1950s through the 1970s	TCE - 0.354 DCE - 0.05 VC - 0.01	TCE - ND DCE - 0.7 VC - 0.02	NA	DCE and VC peaked before starting to decline at end of pilot test
Watertown Industrial Area	Watertown, MA	NA	8 - 12	Unconfined aquifer	NA	NA	NA	NA	Former metal degreasing shop	PCE - 1.0 TCE - 13.0 DCE - 3.0 VC - 0.2	PCE - 0.0085 TCE - 0.095 DCE - 0.163 VC - < 0.2	DCE	Average PCE, TCE, and DCE concentrations were reduced by 99%, 99%, and 95% at 206 days after injection.
Former Manufacturing Site	Walled Lake, MI	NA	NA	NA	NA	NA	NA	NA	NA	DCE - 9.9 VC - 1.9 Ethene - 1.0	DCE - 5.6 VC - 3.2 Ethene - 0.227	NA	Groundwater results showed large amounts of lactic acid fermentation
Unocal Wichita	Wichita, KS	NA	5 - 9	NA	NA	NA	NA	0.03	NA	PCE - 7.0 TCE - 0.84 DCE - 0.56 VC - ND	PCE - 0.04 TCE - 0.54 DCE - 15.0 VC - 1.0	NA	PCE was degraded from 6 mg/L to 0.2 mg/L within 30 days
FMC Corporation Site	San Jose, CA	NA	7 - 10	Semi-confined aquifer	NA	NA	NA	10	Former heavy manufacturing facility	TCE - 3.62 DCE - 0.21 VC - 0.02 Ethene - 0.24	TCE - 3.15 DCE - 0.55 VC - 0.57 Ethene - 2.0	NA	Contaminant concentrations used to calculate mass reductions represent averages of 6 site wells used to monitor this pilot test. Within 6 months of injection the average TCE concentration had been reduced by 13%. DCE, VC, and ethene concentrations increased by 161%, 2750%, and 733% respectively during the same time period.
Hayden Island Cleaners	Portland, OR	NA	25	Unconfined aquifer strongly influenced by the stage of the surrounding Columbia River	NA	0.001	NA	NA	Drycleaning facility	PCE - 0.8 TCE - 0.001 DCE - 0.0034	PCE - 0.2 TCE - 0.035 DCE - 0.070	TCE, DCE	PCE concentrations were reduced by approximately 75% within 20 months of injection, while TCE and DCE concentrations increased within the same time period.
Naval Air Station Dallas	Dallas, TX	NA	8 - 26	Unconfined aquifer	NA	NA	NA	NA	Former petroleum, oil, and lubricants yard	PCE - 0.099 TCE - 0.044 DCE - 0.011	PCE - 0.079 TCE - 0.051 DCE - 0.023	NA	NA
Naval Air Warfare Center	Indianapolis, IN	NA	0	NA	NA	NA	NA	NA	Naval air warfare facility	TCE - 1.0 DCE - 0.202 VC - 0.0003 Ethene - N/A	TCE - 0.54 DCE - ND VC - 0.0005 Ethene - 0.012	NA	NA
Vandalia Manufacturing Facility	Vandalia, IL	NA	8 - 10	Unconfined aquifer	NA	NA	NA	NA	Manufacturing facility	NA	NA	NA	NA
Hurlburt Field	Tallahasse, FL	NA	NA	Confined surficial aquifer	NA	NA	NA	128	Petroleum, oil, and lubricants yard	TCE - 9.5 DCE - 2.0 VC - < 0.1 Ethene - 0.01	TCE - 1.0 DCE - 8.5 VC - 1.5 Ethene - 0.05	NA	Within 1 year of injection TCE concentrations had decreased by approximately 89% while DCE, VC, and ethene concentrations increased by approximately 325%, 1,400%, and 400% respectively. These concentration changes are representative of one well installed approximately 5 feet downgradient of the injection area. The highest concentrations detected during the baseline event were detected at this well.
Industrial Site	NJ	NA	NA	NA	NA	NA	NA	NA	Industrial site	PCE - 5.28 TCE - 0.227 DCE - 0.01 VC - ND	PCE - 0.775 TCE - 0.866 DCE - 3.353 VC - ND	NA	NA
Drycleaning Facility	FL	NA	NA	NA	NA	NA	NA	NA	Drycleaning facility	PCE - 1.2 TCE - 1.5 DCE - 0.4 VC - ND	PCE - ND TCE - ND DCE - ND VC - 0.4	NA	NA

Site Name (Sorted by Substrate)	Site Location	Total Organic Carbon Maximum Pre-Treatment (mg/L)	Total Organic Carbon Maximum Post-Treatment (mg/L)	Dissolved Oxygen Range Pre-Treatment (mg/L)	Dissolved Oxygen Range Post-Treatment (mg/L)	ORP Range Pre-Treatment (mV)	ORP Range Post-Treatment (mV)	pH Range Pre-Treatment (su)	pH Range Post-Treatment (su)	Nitrate Range Pre-Treatment (mg/L)	Nitrate Range Post-Treatment (mg/L)	Ferrous Iron Range Pre-Treatment (mg/L)	Ferrous Iron Range Post-Treatment (mg/L)	Sulfate Range Pre-Treatment (mg/L)	Sulfate Range Post-Treatment (mg/L)	Methane Range Pre-Treatment (mg/L)	Methane Range Post-Treatment (mg/L)
Hydrogen Release Compound (HRC) (Contintued)																	
Former Industrial Filter Manufacturer	Rochester, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Former Landfill Site 7, Duluth International Airport	Duluth, MN	ND	300	NA	NA	88	-40	NA	NA	NA	NA	Approx. 2	Approx. 40	NA	NA	ND	Approx. 1
Watertown Industrial Area	Watertown, MA	NA	1.2 - 5 feet from injection well	NA	0 - 1	NA	-190 to +200	NA	5.8 - 6.8	NA	NA	NA	NA	NA	NA	NA	NA
Former Manufacturing Site	Walled Lake, MI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Unocal Wichita	Wichita, KS	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
FMC Corporation Site	San Jose, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.07 - 23.33	0.28 - 3.87	93 - 270	98 - 270	6 - 106	79 - 524
Hayden Island Cleaners	Portland, OR	NA	NA	NA	NA	< 100	NA	NA	NA	2.1 - 2.3	0.25 - 1.2	0.315	0.02 - 8.74	18-Apr	7.7 - 25	NA	0.0005 - 0.612
Naval Air Station Dallas	Dallas, TX	6.7	12.8	0.3	0.05	102.1	50	6.68	6.62	0.2 N	1.2 N	< 0.03	0.049	1,586	2,410	< 0.01	0.318
Naval Air Warfare Center	Indianapolis, IN	1.2	95.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Vandalia Manufacturing Facility	Vandalia, IL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hurlburt Field	Tallahasse, FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Industrial Site	NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Drycleaning Facility	FL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Thickness (feet)					
Hydrogen Release Compound (HRC) (Continuted)													
Former Industrial Filter Manufacturer	Rochester, NY	Full	HRC; 35 lbs/hole	NA	NA	None	900	15	21 injection points at 5-ft centers using a Geoprobe rig	NA	Site Closed	Quarterly for the first 15 months	Site closure recommneded based on monitoring results
Former Landfill Site 7, Duluth International Airport	Duluth, MN	Pilot	HRC; 180 lbs	NA	NA	None	NA	NA	9 injection points using a Geoprobe rig	April 2000	NA	~ Every 7 weeks	NA
Watertown Industrial Area	Watertown, MA	Pilot	HRC	NA	NA	NA	NA	NA	HRC-containing canisters suspended in injection well	NA	NA	NA	HRC canisters in wells used with a recirculation system
Former Manufacturing Site	Walled Lake, MI	NA	HRC	NA	NA	NA	NA	NA	Geoprobe injection	NA	NA	NA	NA
Unocal Wichita	Wichita, KS	Pilot	HRC	NA	NA	NA	NA	NA	15 injection points	NA	NA	NA	NA
FMC Corporation Site	San Jose, CA	Pilot	HRC; 1040 lbs	NA	NA	None	150	20	6 direct-push points and 5 monitoring wells.	June 1999/1 year pilot test	Full scale planned	4 months after injection, 5, 6, 7 months after injection	Compared top-down to bottom-up injection and found no significant difference in vertical distribution of HRC
Hayden Island Cleaners	Portland, OR	Full	HRC; 1,680 lbs	$6.00	$14,000	None	200	15	34 injection points in 2 rows	NA	Site closed	5 monitoring event performed sporadically through the first 13 months.	Closed to below groundwater MCLs.
Naval Air Station Dallas	Dallas, TX	Pilot	HRC	NA	NA	None	1,500	10	NA	June 2000 - May 2001	Performance monitoring	NA	NA
Naval Air Warfare Center	Indianapolis, IN	Full	HRC	$0.00	NA	None	NA	NA	Injection per Regenesis design	NA	NA	NA	NA
Vandalia Manufacturing Facility	Vandalia, IL	NA	HRC	NA	NA	NA	NA	NA	Barrier configuration	NA	NA	NA	Significant reductions of PCE were observed in monitoring wells located downgradient of HRC barrier
Hurlburt Field	Tallahasse, FL	Full	HRC; 6,000 lbs	$6.00	$36,000	None	2,500	30	24-25 direct injection points installed in a grid with 5 foot spacing. A total of 7 monitoring wells were installed for process monitoring	January 1999/NA	NA/NA	monthly for the first 2 months, quarterly thereafter	The goal of this application was to accelerate reductive dechlorination of TCE in the intermediate aquifer such that remedial goals will be reached in 5 years from the date of application. Degradation of TCE proceeded to completion until the HRC was depleted.
Industrial Site	NJ	Pilot	HRC; 1,080 lbs	NA	NA	NA	NA	NA	23 injection points using Geoprobe rig	NA	NA	NA	NA
Drycleaning Facility	FL	Full	HRC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

BIOREMEDIATION MANUAL
Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description
Hydrogen Release Compound (HRC) (Continued)												
Blackstone River Valley Brownsfield Site	Grafton, MA	No	TCE	Industrial	USEPA	Innovative technology verification	Pilot	June 2000	Willard Murray, Harding ESE 781-245-6606	Ongoing	Murray *et al.*, 2001	NA
Closed Industrial Facility	CO	Yes	PCE, TCE	Industrial	Colorado DPHE	Feasibility study	Pilot	September 1999	Daniel South, Harding ESE, Denver 303-292-5365	Ongoing	South *et al*., 2001	20-25' Unconsolidated silt and clay with occasional lenses of fine sand and sandy clay; severely weathered claystone
Bedrock Site	Princeton, NJ	No	PCE	Industrial	New Jersey DEQ	Accelerate groundwater restoration	Full	2001	Sue Boyle, Haley & Aldrich 585 359-9000	Ongoing	Case *et al*., 2001	Fractured Bedrock
Site 1, Santa Clara County	Santa Clara County, CA	Yes	PCE, TCE	Industrial	Regional Water Quality Control Board - SF	Accelerate groundwater restoration	Pilot, Full	December 1999/September 2001	Pawan Sharma, CDM 303-292-5365	Pilot Completed, expanded application in September 2001	Sharma *et al*., 2001	Interbedded layers of clay, silty sand, and sand (clay is predominant soil type above water-bearing zone)
Site 2, Santa Clara County	Santa Clara County, CA	Yes	PCE, TCE, DCE	Industrial	Regional Water Quality Control Board - SF	Accelerate groundwater restoration in source area	Pilot, Full	October 2000/June 2001	Pawan Sharma, CDM 303-292-5365	Pilot and expanded test completed	Sharma *et al*., 2001	Interbedded layers of clay, silty sand, and sand (clay is predominant soil type above water-bearing zone)
Tosco Manufacturing Facility	Burien, WA	Yes	PCE, TCE, DCE	Industrial	Washington DEQ	Accelerate groundwater restoration at hotspots	Full	August 2000	John Meyer, Environmental Resolutions 206-706-2341	Ongoing	Regenesis Case History #H 3.1	NA
Strip Mall Dry Cleaner	Kent, WA	Yes	PCE, TCE	Industrial	Washington DEQ	Groundwater remediation	Full	December 1998	Jim Ruef, Environmental Associates 425-455-9025	No-Further Action Letter	Regenesis Case History #H 2.8	NA
Dayco Manufacturing Facility	Eldora, IA	Yes	TCE	Industrial	Iowa DEP	Feasibility study for HRC in a barrier configuration	Pilot	February 1998	Jack Sheldon, Montgomery Watson Harza 515-253-0830	Ongoing	Sheldon and Armstrong, 2000; Sheldon and Armstrong, 2002	Stratigraphic consists of approximately 30 feet of dense clay overlying approximately 20 feet of sand. The sand is underlain by silt.
Moen Manufacturing Facility	Elyria, OH	Yes	DCE, VC	Industrial	Ohio DEQ	Feasibility study to compare anaerobic and aerobic degradation of DCE and VC	Pilot	July 1999	Thomas Cornuet, Weston 610-701-7360	Ongoing, full-scale application was planned.	Cornuet, *et al*., 2000	Approximately 5 to 8 feet of overburden overlying approximately 30 feet of fine to medium grained sandstone and shale bedrock. The sandstone is underlain by a low permeability shale with thin siltstone layers near the sandstone - shale contact
Springdale Drycleaners	Portland, OR	Yes	PCE, TCE	Industrial	Oregon DEQ	DNAPL and source area remediation	Pilot	December 1999	Kevin Parrett, Oregon DEQ 503-229-6748	Scheduled full scale HRC application in the fall of 2001	State Coalition for Remediation of Drycleaners (Springdale, OR); Parrett K. and Sandefur C. A., 2002	Sandy , silty, clay from groundsurface to approximately 12 feet below ground surface underlain by approximately 10 feet of silty clay.

Site Name (Sorted by Substrate)	Site Location	Soil TOC (mg/kg)	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments
Hydrogen Release Compound (HRC) (Continued)													
Blackstone River Valley Brownsfield Site	Grafton, MA	NA	NA	NA	NA	NA	NA	NA	NA	TCE - 1.0 DCE - 0.4 VC - < 0.005	TCE - 0.2 DCE - 1.2 VC - < 0.005	NA	NA
Closed Industrial Facility	CO	NA	7 - 10	Impacted aquifer consists of unconsolidated silt and clay, and is 20 to 25 feet thick.	2.4 to 5	NA	NA	183	Former industrial facility	PCE - 9.0 TCE - 1.4 DCE - 0.56 VC - 0.29 Ethene - < 0.01	PCE - 0.5 TCE - 0.68 DCE - 17.0 VC - 2.4 Ethene - 1.31	NA	Within first month of HRC injection, PCE concentrations decreased by up to 97% in the source zone.
Bedrock Site	Princeton, NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site 1, Santa Clara County	Santa Clara County, CA	NA	7 - 10	NA	2.8 to 28	0.001 to 0.002	15	55	Manufacturing facility	PCE - 0.027 TCE - 11.0 DCE - 0.595 VC - < 0.05 Ethene - 0.000026	PCE - < 0.02 TCE - 0.071 DCE - 5.23 VC - 0.014 Ethene - 0.000447	NA	NA
Site 2, Santa Clara County	Santa Clara County, CA	NA	7 - 10	NA	28 to 141	0.001 to 0.002	30	1825	Manufacturing facilities	PCE - 0.22 TCE - 0.82 DCE - 3.0 VC - 0.3 Ethene - 0.021	PCE - 0.023 TCE - 0.94 DCE - 1.516 VC - 1.4 Ethene - 1.2	NA	NA
Tosco Manufacturing Facility	Burien, WA	NA	5 - 9	NA	NA	NA	NA	0.22	Manufacturing facility	PCE - 11.4 TCE - 1.7	PCE - 3.1 TCE - 2.5	NA	Within 159 days following injection the PCE concentration in one well was reduced by 73% while the TCE concentration in the same well increased by 44%. DCE and VC data for this site were not provided.
Strip Mall Dry Cleaner	Kent, WA	NA	NA	NA	NA	NA	NA	274	Drycleaner	PCE - 67.4 TCE - 11.7 DCE - 0.36 VC - .060 Ethene - < 0.005	PCE - 0.034 TCE - 0.017 DCE - 0.02 VC - 0.07 Ethene - < 0.005	NA	PCE and TCE concentrations had been reduced by nearly 100% within 14 months of injection at one source area well. DCE and VC concentrations had been reduced by 44% and 88% respectively in one downgradient well within 2 years of injection.
Dayco Manufacturing Facility	Eldora, IA	NA	NA	Surficial aquifer perched above a silt layer and confined below a dense clay layer.	NA	NA	NA	NA	Manufacturing facility	TCE - 2.23 DCE - 5.03 VC - 0.134	TCE - 0.56 DCE - 1.71 VC - < 0.001	NA	Within 35 weeks of injection TCE, DCE, and VC concentrations were reduced by approximately 75%, 66%, and nearly 100% respectively. These reductions were observed in one well approximately 5 feet downgradient from the injection well. Contaminant concentration data from wells further downgradient from the injection area were not provided.
Moen Manufacturing Facility	Elyria, OH	NA	9.5 - 11.5	Fractured sandstone bedrock aquifer	4	0.008	15	75	Manufacturing facility	DCE - 0.59 VC - 0.21	DCE - 0.02 VC - 0.01	NA	Original COC was TCE but nearly all TCE mass has been reduced naturally to DCE and VC. TCE has not been detected onsite at concentrations exceeding the MCL for several years. Within 180 days of injection DCE and VC concentrations in one well 25 feet downgradient from the injection area were reduced by approximately 97% and 94% respectively.
Springdale Drycleaners	Portland, OR	NA	20	unconfined surficial aquifer	NA	0.0001	NA	NA	Drycleaner	PCE - 98 TCE - 35.9 DCE - < 0.005 VC - < 0.005 Ethene - NA	PCE - < 0.25 TCE - 0.30 DCE - 43.9 VC - 9.5 Ethene - NA	*Cis*-1,2-DCE, *trans*-1,2-DCE, VC	Within 18 months after the pilot scale injection PCE and TCE concentrations had decreased by 99% while DCE and VC concentrations had increased significantly in one well installed an unknown distance from the injection area. The concentration trend for DCE is downward while the concentration trend for VC is upward. These reduction calculations represent the source area application. No ethane concentration data was provided for this site.

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Total Organic Carbon		Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane	
		Maximum Pre-Treatment (mg/L)	Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)
Hydrogen Release Compound (HRC) (Continued)																	
Blackstone River Valley Brownsfield Site	Grafton, MA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Closed Industrial Facility	CO	NA	NA	0.75 to 2.68	NA	-25 to +269	-429 to +335	NA	NA	< 0.1 to 0.4	NA	NA	NA	57 to 75	< 10	NA	NA
Bedrock Site	Princeton, NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site 1, Santa Clara County	Santa Clara County, CA	5	240	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site 2, Santa Clara County	Santa Clara County, CA	4.1	1,600	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tosco Manufacturing Facility	Burien, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Strip Mall Dry Cleaner	Kent, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dayco Manufacturing Facility	Eldora, IA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	25.9	21.4	NA	NA
Moen Manufacturing Facility	Elyria, OH	9	880 - 30 days after injection 310 - 180 days after injection	NA	NA	NA	NA	6.45	5.62	NA	NA	24	53	310	62	NA	NA
Springdale Drycleaners	Portland, OR	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

APPENDIX B - ENHANCED BIOREMEDIATION DATABASE

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area		System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
							Surface Area (sq. ft)	Thickness (feet)					
Hydrogen Release Compound (HRC) (Continued)													
Blackstone River Valley Brownsfield Site	Grafton, MA	Pilot	HRC	NA	NA	NA	NA	NA	NA	NA	NA	NA	USEPA Superfund Innovative Technology Site (SITE) Program site
Closed Industrial Facility	CO	Pilot	HRC; 1,200 lbs	NA	NA	None	NA	25	Polymer injected at nine locations using Strataprobe rig	September '99; 1 year	NA	NA	VOC data indicate reductive dechlorination was accelerated
Bedrock Site	Princeton, NJ	NA	HRC	NA	NA	NA	NA	NA	Blast-fractured trenches in bedrock in two parallel trenches, directing groundwater into treatment zones of reactive iron and HRC treatment	NA	NA	NA	Demonstrated effective delivery of HRC to a fractured bedrock environment
Site 1, Santa Clara County	Santa Clara County, CA	Pilot	HRC and sodium lactate; 6 lbs/ft	$17.50	NA	None	NA	NA	Injection by Geoprobe rig	NA	NA	NA	Additional injections 1.5 years later. Both HRC and fast HRC primer accelerated biodegradation of CAHs. HRC primer rapidly reduced competing electron acceptors also resulted in significant methane production. Bioaugmentation being considered.
Site 2, Santa Clara County	Santa Clara County, CA	Pilot	HRC - standard and primer; 3 lbs/ft	$19.00	NA	None	NA	NA	Injection using Geoprobe rig. First, HRC-primer (fast-release) applied, and then the standard polymer (slow-release) is injected few inches away.	NA	NA	NA	Additional injections to source area after 9 months. Both fast and slow release HRC products were shown to stimulate anaerobic biodegradation of CAHs
Tosco Manufacturing Facility	Burien, WA	Full	HRC, 2,475 pounds	$6.36	$15,750	None	4,100	15	33 direct injection points. HRC was injected at a rate of 5 pounds per foot from 5 to 20 feet below ground surface.	November, 2000/ unknown	NA	Bimonthly for the first 7 months	Overall, PCE in 6 wells decreased an average of 70 percent. DCE, VC, and ethene concentration data were not published for this site.
Strip Mall Dry Cleaner	Kent, WA	Full	Full - 1,180 lb HRC	NA	NA	None	2,000	NA	55 direct injection points and three monitoring wells.	NA	NA	Quarterly for the first 12 months, sporadically thereafter.	Closed with no-further-action.
Dayco Manufacturing Facility	Eldora, IA	Pilot	HRC, delivered via 4 4-foot canister implants installed successively in one well. The total mass of HRC emplaced was not published.	NA	NA	None	250	15	HRC was emplaced using 4 foot long perforated poly carbonate canisters. A total of 4 canisters were installed successively in four treatment event spanning 1 week. A total of 8 monitoring wells were used for process monitoring activities.	February 1998/Pilot test lasted 35 weeks	NA	Samples were collected at 2, 4, 8, 11, 24, and 35 weeks post emplacement	This application was designed to test emplacement of HRC from poly carbonate canisters as a method to develop a way to employ HC as a barrier wall. After 1 year, total VOC concentrations in shallow aquifer decreased by 50%. VOCs in deeper aquifer fluctuated over a greater range.
Moen Manufacturing Facility	Elyria, OH	Pilot	ORC and HRC tested in two identical side by side field applications	NA	NA	None	450	30	Two pilot test arrays consisting of 4 injection wells and 3 monitoring wells per array	July 1999/ 180 day pilot tests with design of full scale application to follow	Full scale application is currently in the design stage.	monthly during pilot testing	This application was a side by side comparison study of ORC to HRC for the dechlorination of DCE and VC. DCE and VC at this site result from natural degradation of TCE.
Springdale Drycleaners	Portland, OR	Pilot	HRC, 3,040 lb	NA	NA	NA	45,000	3	A residual source area was treated with 5 injection points (80 lb HRC per point) and the downgradient dissolved phase plume area was treated with 22 injection points (120 lb HRC per point)	NA/2-3 years	OR DEQ is currently monitoring the pilot test application in consideration of a full scale application	Monitoring will occur quarterly for 2-3 years following application	NA

Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description	Soil TOC (mg/kg)
Hydrogen Release Compound (HRC) (Continued)													
Reichhold Chemicals	Tacoma, WA	Yes	Chlorinated Phenols	Industrial	NA	Groundwater remediation	Pilot	NA	Steve Koenigsberg, Regenesis	NA	Regenesis Case History #H 2.2	Approximately 400 feet of fine grained marine sediments	NA
Acton Mickelson Ordinance Facility	Hollister, CA	Yes	Perchlorate, Hexavalent Chromium, Freon-113	Industrial	California RWQCB	Groundwater remediation of perchlorate	Full	December 2000	Jack Peabody, Regenesis 925-944-5566	Ongoing	Regenesis Case History #H 2.1	Fine to medium silty sand	NA
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Yes	2,4,6-trinitrotoluene (2,4,6-TNT), 1,3,5-trinitrobenzene (1,3,5-TNB), 2,4-dinitrotoluene (2-4,DNT), hexahydro-1,3,5-tritro-1,3,5-triazone (RDX)	DoD	Colorado DPHE, USEPA	Groundwater remediation, plume containment	Pilot	February 2000	Paul Barnes, Earth Tech 719-545-2352	Below MCLs	Regenesis Case History #H 2.0	Sand and clayey sand overlain by a clay to silty sand confining or semi-confining unit.	NA
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Yes	TCE	DoD	Colorado DPHE, USEPA	Groundwater restoration	Pilot	February 2001	Scott Schankweiler, Versar 303-452-5700	Ongoing	Schankweiler *et al*., 2002	Alluvial aquifer	NA
Manufacturing Facility	Crozet, VA	Yes	TCE	Industrial	Virginia DEQ	Feasibility study for a bedrock site	Pilot	December 1999	Mark Eliason, Weston 610-701-3145	Below MCLs	Regenesis Case History #H 1.7	Fractured crystalline bedrock	NA
Manufacturing Facility	NJ	Yes	TCE	Industrial	New Jersey DEQ	Feasibility study	Pilot	NA	Steve Koenigsberg, Regenesis	NA	Regenesis Case History #H 1.5	Medium to coarse grained sand	NA
Flemington Manufacturing Facility	Flemington, NJ	Yes	PCE, TCE, DCE	Industrial	New Jersey DEQ	Feasibility study	Pilot	March 2001	Michael Kozar, O'Brien & Gere Engineers Inc. 215-628-9100	Ongoing	Regenesis Case History #H 1.6; Kozar *et al*., 2002	NA	NA
Cedarburg Drycleaning Facility	Cedarburg, WI	No	PCE	Industrial	Wisconsin DNR	Technology demonstration	Pilot	May 1998	John Sheldon, Montgomery Watson Harza 515-253-0830	Went to full-scale, closed	Sheldon *et al.*, 1999; Regenesis Case History #H 1.1	Approximately 1.8 to 5 feet of sand confined, above and below, by thick silt and clay units.	NA
Japanese Electrical Plant	Japan	Yes	PCE, TCE, DCE	Industrial	NA	Groundwater remediation	Pilot	2000	Makoto Nakashima, Kokusia Kogyo Co.	1 year pilot test was completed.	Nakashima M. and Nishigaki M., 2000	Gravel and cobble aquifer matrix perched above an aquitard. The aquifer - aquitard interface is approximately 16 feet below ground surface	NA
Charleston Naval Complex	Charleston, SC	No	PCE	Navy	USEPA	Technology Demonstration	Full	May 2001	William Elliot, CH2M Hill 352-335-991	Ongoing	Elliot, *et al*., 2002	NA	NA
Coopervision Manufacturing Facility	Scottsville, NY	Yes	1,1,1-TCA	Industrial	New York State Department of Environmental Conservation	Groundwater remediation	Pilot	July 2001	Vincent Dick, Haley & Aldrich Rochester NY, 716-359-9000	Injection attempts using direct push failed, mud rotary drilling was used	Case *et al*., 2001; Dick *et al.*, 2002	Very dense till consisting of clayey silts and some sand	NA

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments	Total Orga Maximum Pre-Treatment (mg/L)
Hydrogen Release Compound (HRC) (Continued)													
Reichhold Chemicals	Tacoma, WA	NA	Unconfined aquifer	NA	NA	NA	NA	Pentachlorophenol and treated fiber product plant	Pentachlorophenol - 1.6 2,3,4,6-Tetrachlorophenol - 0.2 2,4,5-Trichlorophenol - < 0.05 2,4-Dichlorophenol - < 0.05	Pentachlorophenol - 0.54 2,3,4,6-Tetrachlorophenol - 0.1 2,4,5-Trichlorophenol - < 0.05 2,4-Dichlorophenol - < 0.05	Aroclor-1248, molybdenum, lead	Within 280 days after injection PCP and 2,3,4,6-TCP concentrations had been reduced by approximately 66% and 50% respectively at one monitoring well installed approximately 10 downgradient from the line of injection wells.	NA
Acton Mickelson Ordinance Facility	Hollister, CA	NA	Shallow unconfined aquifer	NA	NA	NA	26	Ordinance production plant	Perchlorate - 7.5 Chrome-6 - 0.16 Freon-113 - 0.25	Perchlorate - 1.0 Chrome-6 - < 0.1 Freon-113 - 0.02	NA	Within 80 days after injection perchlorate, hexavalent chromium, and freon-1113 concentrations had been reduced by approximately 87%, nearly 100%, and 92% respectively at one well installed within the injection grid. No analytical data was provided for wells installed downgradient from the injection area.	NA
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	37	Confined surficial aquifer present in the sand and clayey sand unit	NA	NA	NA	18,000	Explosives and ordinance production	2,4-DNT - 0.0037 RDX - 0.0093 1,3,5-TNB - 0.231 Hydrazine - 0.001	2,4-DNT - 0.0003 RDX - < 0.0001 1,3,5-TNB - 0.005 Hydrazine - NA	Nitrate, Hydrazine	Within approximately 105 days following injection 2,4 DNT, RDX, and 1,3,5-TNB concentrations had decreased by approximately 89%, 99%, and 98% respectively. These reduction calculations represent average concentrations calculated from 4 downgradient monitoring wells. Concentration data was provided for only the 4 wells closest to the injection area (approximately 30 feet downgradient) out of a total of 15 monitoring wells used for process monitoring.	NA
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	NA	Alluvial aquifer	NA	NA	NA	1,825 to 18,250	NA	NA	NA	NA	Contaminanat data was minimal during irst 3 months of pilot test. However, and order of magnitude reduction in TCE concentration was observed 50 feet downgradient of treatment zone after 11 months.	NA
Manufacturing Facility	Crozet, VA	22 - 32	Bedrock aquifer	NA	NA	NA	NA	Manufacturing facility	TCE - 0.225 DCE - 0.125 VC - < 0.005 Ethene - < 0.005	TCE - < 0.005 DCE - 0.08 VC - 0.05 Ethene - 0.05	NA	Within 13 months of injection TCE and DCE concentrations had decreased by approximately 98% and 94% respectively while VC and ethene concentrations had increased by approximately 900% in one monitoring well installed approximately 10 feet downgradient from the injection wells.	NA
Manufacturing Facility	NJ	5	unconfined surficial aquifer	NA	NA	NA	365	Manufacturing facility	NA	NA	NA	Contaminant concentration data was not provided.	NA
Flemington Manufacturing Facility	Flemington, NJ	NA	NA	NA	NA	NA	NA	Manufacturing facility	PCE - .011 TCE - 0.10 DCE - 0.05 VC - NA Ethene - NA	PCE - 0.004 TCE - 0.009 DCE - 0.022 VC - NA Ethene - NA	NA	Within 80 days of injection PCE, TCE, and DCE concentrations had been reduced by approximately 64%, 10%, and 56% respectively in one monitoring well installed an unknown distance downgradient from the emplacement area.	NA
Cedarburg Drycleaning Facility	Cedarburg, WI	NA	Confined sand aquifer	NA	NA	NA	11	Drycleaning facility	NA	NA	NA	Contaminant concentration data was not provided.	NA
Japanese Electrical Plant	Japan	7	Unconfined gravel aquifer	NA	NA	NA	NA	Electrical plant	NA	NA	NA	HRC accelerated the natural attenuation process.	NA
Charleston Naval Complex	Charleston, SC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	In one area, PCE concentrations are below detection limits in the shallow, intermediate and deep aquifer. In the second area, PCE concentrations decreased moderately.	NA
Coopervision Manufacturing Facility	Scottsville, NY	5	unconfined dense till aquifer	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

APPENDIX B - ENHANCED BIOREMEDIATION DATABASE

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	nic Carbon Maximum Post-Treatment (mg/L)	Dissolved Oxygen Range Pre-Treatment (mg/L)	Dissolved Oxygen Range Post-Treatment (mg/L)	ORP Range Pre-Treatment (mV)	ORP Range Post-Treatment (mV)	pH Range Pre-Treatment (su)	pH Range Post-Treatment (su)	Nitrate Range Pre-Treatment (mg/L)	Nitrate Range Post-Treatment (mg/L)	Ferrous Iron Range Pre-Treatment (mg/L)	Ferrous Iron Range Post-Treatment (mg/L)	Sulfate Range Pre-Treatment (mg/L)	Sulfate Range Post-Treatment (mg/L)	Methane Range Pre-Treatment (mg/L)	Methane Range Post-Treatment (mg/L)	Scale of Application	Substrate Type, Amount, and Concentration
Hydrogen Release Compound (HRC) (Continued)																		
Reichhold Chemicals	Tacoma, WA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, 3,870 lb
Acton Mickelson Ordinance Facility	Hollister, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, 660 lb
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	NA	5.05	NA	+138	NA	7.41	NA	6.1	NA	0.04	NA	229	NA	NA	NA	Pilot	HRC, NA
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC
Manufacturing Facility	Crozet, VA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, 420 lb
Manufacturing Facility	NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, 500 lb
Flemington Manufacturing Facility	Flemington, NJ	NA	NA	NA	NA	NA	NA	NA	NA	NA	35.9	24.5	54.5	36.8	NA	NA	Pilot	HRC, NA
Cedarburg Drycleaning Facility	Cedarburg, WI	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, 240 lb
Japanese Electrical Plant	Japan	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, 600 lb
Charleston Naval Complex	Charleston, SC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	HRC, NA
Coopervision Manufacturing Facility	Scottsville, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, NA

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area Surface Area (sq. ft)	Treatment Area Thickness (feet)	System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
Hydrogen Release Compound (HRC) (Continued)													
Reichhold Chemicals	Tacoma, WA	Pilot	HRC, 3,870 lb	NA	NA	NA	4,300	5	A single line of 43 injection points were installed at 10 foot intervals. Two monitoring wells (10 feet upgradient and 10 feet downgradient) were used to monitor performance	NA/280 days	NA	monthly for the first 10 months.	This pilot test was designed to test the effectiveness of HRC to remediate phenolic contaminants in groundwater
Acton Mickelson Ordinance Facility	Hollister, CA	Pilot	HRC, 660 lb	NA	NA	NA	1,200	4	25 injection points installed in a grid on 5 foot centers. 6 monitoring wells installed for process monitoring	NA/NA	NA	Process monitoring samples were collected 50 and 80 days after injection	Closed to below MCLs.
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Pilot	HRC, NA	NA	NA	NA	350	NA	HRC was injected into 30 locations installed in a line. A total of 15 monitoring wells were installed for process monitoring sampling.	NA/NA	NA/NA	Process monitoring samples were collected at 34, 57, 85, and 105 days following injection	This pilot test was designed to test the effectiveness of HRC to remediate nitrates and explosive compounds in groundwater.
Pueblo Chemical Depot - SWMU-14	Pueblo, CO	Pilot	HRC	NA	NA	NA	NA	NA	Barrier configuration	NA	Ongoing	NA	Evaluated effectiveness of HRC as a barrier type treatment in a high-flow aquifer
Manufacturing Facility	Crozet, VA	Pilot	HRC, 420 lb	$21.43	$9,000	NA	50	6	3 injection wells spaced approximately 5 feet apart with one monitoring well installed approximately 10 feet downgradient from the injection wells.	NA/NA	Full scale HRC application is being considered	Monthly for the first 3 months, quarterly thereafter	HRC was shown to be effective at treating chlorinated solvents within the fractured bedrock system.
Manufacturing Facility	NJ	Pilot	HRC, 500 lb	$7.50	$3,750	NA	4,900	15	15 direct push points installed in a barrier configuration approximately 5 feet apart	NA/NA	NA	biweekly for the first 4 months	NA
Flemington Manufacturing Facility	Flemington, NJ	Pilot	HRC, NA	NA	NA	NA	NA	12	Three 3.5-inch by 4-foot long PVC canisters filled with gelled HRC were installed in a single 4-inch well. An unknown number of monitoring wells were installed for process monitoring.	NA/NA	NA/NA	biweekly for the first month, monthly thereafter	This application involved installing canisters of gelled HRC in a well as a slowly soluble and therefore longer term HRC source. This site is very similar to the Central US Manufacturing Facility application
Cedarburg Drycleaning Facility	Cedarburg, WI	Pilot	HRC, 240 lb	$8.00	$1,920	None	60	3	12 direct injection points installed in a 3.5 foot grid. 8 monitoring wells, 1 well installed within the grid and 7 installed 2, 7, and 12 feet downgradient of the injection grid.	NA/NA	NA/NA	Quarterly for the first 9 months.	First commercial grid application of HRC
Japanese Electrical Plant	Japan	Pilot	HRC, 600 lb	NA	NA	NA	500	7	7 injection points in two rows spaced approximately 13 feet apart. Row spacing was also approximately 13 feet. Two monitoring wells were installed, 1 upgradient and 1 downgradient.	NA/1 year	NA/NA	Quarterly	NA
Charleston Naval Complex	Charleston, SC	NA	HRC, NA	NA	NA	NA	NA	44	NA	NA	NA	NA	NA
Coopervision Manufacturing Facility	Scottsville, NY	Pilot	HRC, NA	NA	NA	NA	NA	33	NA	July 2001 / efforts to inject using direct push were unsuccessful	re-injection using mud rotary is planned	NA	NA

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description	Soil TOC (mg/kg)
Hydrogen Release Compound (HRC) (Continued)													
Invensys Control	Old Saybrook, CT	Yes	PCE	Industrial	Connecticut Department of Environmental Protection	Groundwater restoration to facilitate property transfer	Pilot, Full	Pilot - December 1999 Full - September 2000	Dale Skoff, Earth Tech, Inc. 724 934-1666	Following the success of the pilot test a full scale system was designed by Earth Tech and approved by CTDEP. The full scale was	Skoff, *et al.* , 2002	Shallow silty sand outwash plain unit underlain by a deep gravel outwash unit	NA
Manufacturing Facility	Brighton, NY	Yes	TCE	Industrial	NA	Groundwater Restoration	Pilot	NA	Steve Koenigsberg, Regenesis	NA	Regenesis Case History #H 1.2	Very tight clay rich glacial till	NA
Rocky Flats Environmental Technology Site	Golden, CO	No	PCE	DoE	USEPA	Groundwater remediation	Pilot	February 2001	Annette Primrose, Kaiser Hill 303-966-4385	Process monitoring is ongoing	Primrose *et al.* , 2002	Low permeability clay alluvium overlying weathered bedrock	NA
Arlington Cleaners	Arlington, TX	Yes	PCE, TCE, DCE, VC	Industrial	TNRCC	Groundwater remediation under voluntary cleanup program	Full	May 2000	Rick Railsback, ProGEA Inc Dallas, TX 972-488-3540	Conditional closure under TNRCC	Railsback *et al*., 2002	NA	NA
Cookville Manufacturing Facility	Cookville, TN	No	PCE, TCE	Industrial	Tennessee Voluntary Clean-up Oversight and Assistance Program (VCOAP)	Remediate PCE in goundwater to below federal MCLs at property boundary	Pilot/Full	January 2000	Willard Murray, Diana Tremaine, Harding ESE, 781-245-6606	Ongoing	Murray *et al* ., 2002	Tight Clay Soils	NA
Rice University Laboratory Study	Rice University, TX	No	PCE	NA	NA	Technology demonstration on DNAPL dissolution	Bench	2001	Joseph Hughes and David Adamson, Rice University, 713-348-5903	Completed	Adamson *et al.* , 2002	NA	NA
River Terrace	Kanai, AK	No	PCE, TCE	Industrial	Alaska Department of Environmental Quality	Groundwater remediation	Full	September 2000	Jack Paris, Oasis Environmental, 907-258-4880	Ongoing	Koenigsberg *et al* ., 2002	NA	NA
Massachusetts Military Reservation (MMR)	MA	No	ADNT, RDX	Military	AMEC	Technology demonstration for explosives and perchlorate	Bench	2001	Paul Barnes, Earth Tech, 719-545-2352	Completed	Barnes *et al* ., 2002	NA	NA
West Union	West Union , SC	No	TCE	Industrial	South Carolina Dept. Health & Environmental Control	Groundater restoration at a bedrock site	Full	May 2001	Andrew Baird, Schlumberger, 864-232-1566	Ongoing	Baird *et al.* , 2002; Klutz *et al* ., 2002	Saprolite and Bedrock Aquifer	NA
Edible Oils													
Former Zipper Manufacturing Facility	Newport News, VA	Yes	PCE, TCE, DCE	Industrial	Virginia DEQ	Risk-based closure	Pilot	April 2000	Neil Peters, ERM West 410-266-0006	Evaluate full-scale remediation	Skladany *et al.* , 2001	NA	NA
OU2, Defense Depot Hill Utah	Ogden, UT	No	TCE	DoD	EPA	Technology demonstration	Pilot	July 1999	Dave Brown, Parsons 801-572-5999	NA	NA	NA	NA
OU4, Defense Depot Hill Utah	Ogden, UT	No	NA	DoD	EPA	NA	NA	NA	Dave Brown, Parsons 801-572-5999	NA	NA	NA	NA
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	Yes	PCE, TCE, VC	Air Force	Florida DEP, EPA	Technology demonstration	Pilot, Full	Pilot - June 1999 Full - July 2000	Bruce Henry, Parsons 303-831-8100	Performance monitoring	Parsons, 2002d	Sand and silty sand with some shell fragments and organic matter to 35' bgs, clay layer at 36 to 42 feet bgs	NA
Site N-6, Former NSA Mid-South	Millington, TN	Yes	TCE, DCE, CT	Navy	Tennessee DEC and EA	Field feasibility study	Pilot	August 2000	Bruce Henry, Parsons 303-831-8100	Performance monitoring	Parsons, 2002e	Fluvial deposits from 40 to 90 feet bgs consisting of sand, silty sand, and clay stringers	<25
Site SS-015, Travis AFB	Travis AFB, CA	Yes	PCE, TCE	Air Force	California RWQCB	Technology demonstration	Pilot, Full	Pilot - April 1999 Full - December 2000	Bruce Henry, Parsons 303-831-8100	Performance monitoring	Parsons, 2002c	Silty clay with thin layers of silt and silty sand	NA

Site Name (Sorted by Substrate)	Site Location	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments	Total Orga Maximum Pre-Treatment (mg/L)
Hydrogen Release Compound (HRC) (Continued)													
Invensys Control	Old Saybrook, CT	NA	unconfined silty sand aquifer	0.03 - 1.0	NA	NA	NA	Electronics Manufacturing Plant	PCE - 13.9	PCE - 0.01	NA	Within 9 months after the pilot scale injection PCE concentrations had decreased by 99% in one well installed an unknown distance from the injection area. No other data has been provided for this site.	NA
Manufacturing Facility	Brighton, NY	5	Unconfined glacial till aquifer	0.01	NA	NA	NA	Manufacturing facility	NA	NA	NA	NA	NA
Rocky Flats Environmental Technology Site	Golden, CO	20-May	Unconfined surficial aquifer	NA	NA	NA	100	NA	NA	NA	NA	NA	NA
Arlington Cleaners	Arlington, TX	7-Jan	NA	NA	NA	NA	NA	Drycleaning Facility	PCE - 4.5 TCE - 1.0 DCE - 7.3 VC - 0.87 Ethene - NA	PCE - 0.41 TCE - 0.09 DCE - 0.44 VC - 0.13 Ethene - NA	NA	Within 18 months after the pilot scale injection PCE, TCE, DCE, and VC concentrations had decreased by 98%, 91%, 94%, and 85% respectively at one well installed within or downgradient from the injection area. No ethane concentration data was provided for this site.	NA
Cookville Manufacturing Facility	Cookville, TN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Levels of TCE and DCE in range of milligrams per liter	NA
Rice University Laboratory Study	Rice University, TX	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Accelerated DNAPL dissolution and biodegradation	NA
River Terrace	Kanai, AK	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	HRC was effective at degradation of PCE and TCE in upper and lower plume. However, DCE stalled in lower plume due to lack of appropriate microbes.	NA
Massachusetts Military Reservation (MMR)	MA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
West Union	West Union , SC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Edible Oils													
Former Zipper Manufacturing Facility	Newport News, VA	1.5	Shallow coastal plain aquifer, extending from 5' bgs with confining layer at ~10' bgs	0.09 to 1.1	NA	NA	3	Manufacturing facility	PCE - 120.0 TCE - 8.0 DCE - 14.0 VC - 1.3 Ethene - 0.623	PCE - 34.0 TCE - 11.0 DCE - 27.0 VC - 5.3 Ethene - 0.87	1,2-DCA	NA	910
OU2, Defense Depot Hill Utah	Ogden, UT	10	Unconfined aquifer with confining layer at 25 feet bgs	Delayed	NA	30 (est.)	100	NA	NA	NA	NA	NA	<8.0
OU4, Defense Depot Hill Utah	Ogden, UT	NA	NA	Delayed	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	4 - 6	Unconfined aquifer 30 to 35 feet thick	100 to 500	0.0003 to 0.0007	25 (est.)	40 to 500	Aircraft maintenance and cleaning	PCE - 1.8 TCE - 260 DCE - 78 VC - 0.95 Ethene - 0.62	PCE - 0.048 TCE - 310 DCE - 190 VC - 13 Ethene - 0.05	None	None	54.9
Site N-6, Former NSA Mid-South	Millington, TN	47 - 79	Unconfined to semi-confined aquifer 80 to 100 feet thick	44 to 68	0.004	27 (est.)	45 (upper) 22 (lower)	Aircraft maintenance and cleaning	TCE - 1.8 DCE - 0.034 VC - ND Ethene - 0.005	TCE - 1.2 DCE - 0.25 VC - ND Ethene - 0.0003	CT: 0.26 mg/L	None	<5.0
Site SS-015, Travis AFB	Travis AFB, CA	8 - 11	Unconfined overburden aquifer approximately 20 to 25 feet thick	0.003 to 0.04	0.003	10 (est.)	0.005 to 0.85	Aircraft maintenance and cleaning	PCE - 1.0 TCE - 4.2 DCE - 13 VC - 17 Ethene - 0.47	PCE - 0.43 TCE - 2.2 DCE - 4.0 VC - 0.55 Ethene - 0.67	Benzene: 0.012 mg/L Chlorobenzene: 0.50 mg/L	None	6.1

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	nic Carbon	Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane		Scale of Application	Substrate Type, Amount, and Concentration
		Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)		
Hydrogen Release Compound (HRC) (Continued)																		
Invensys Control	Old Saybrook, CT	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot and Full	Pilot - HRC, NA Full - HRC, 11,000 lb
Manufacturing Facility	Brighton, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, 500 lb
Rocky Flats Environmental Technology Site	Golden, CO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	HRC, 800 lb
Arlington Cleaners	Arlington, TX	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Full	HRC, 7,000 lb
Cookville Manufacturing Facility	Cookville, TN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rice University Laboratory Study	Rice University, TX	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
River Terrace	Kanai, AK	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Massachusetts Military Reservation (MMR)	MA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
West Union	West Union , SC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Edible Oils																		
Former Zipper Manufacturing Facility	Newport News, VA	560	< 1	< 1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.6 - 9.2	0.92 - 5.4	Pilot	Vegetable Oil; 4,800 lbs
OU2, Defense Depot Hill Utah	Ogden, UT	37 - 610	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	Vegetable Oil
OU4, Defense Depot Hill Utah	Ogden, UT	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Vegetable Oil
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	6.2	<0.1 to 0.23	0.09 to 0.20	-35 to -154	-126 to -191	7.03 to 7.84	7.04 to 7.23	<0.05 to 0.10	0.02J	1.96 to 2.05	3.19 to 4.0	19.2 to 29.9	2.9 to 32	0.09 to 0.96	0.22 to 0.25	Pilot, Full	Vegetable Oil
Site N-6, Former NSA Mid-South	Millington, TN	2,400	0.2 to 1.4	0.4 to 6.1	+253 to -359	+66 to -130	6.26 to 6.99	5.30 to 6.82	0.051 to 1.7	0.050J to 1.7	0.23 to 3.5	<0.01 to 16.5	<1 to 19	<1	8.6 to 108	25 to 13,000	Pilot	Vegetable Oil
Site SS-015, Travis AFB	Travis AFB, CA	620	0.42 to 6.58	0.42 to 4.23	+52 to +264	-63 to -336	6.23 to 6.94	6.00 to 7.06	<0.05 to 0.27	<0.1	0.2 to 2.2	<0.01 to 11	Unknown	170 to 3100	9.9 to 113	4.5 to 3,500	Pilot, Full	Vegetable oil

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area Surface Area (sq. ft)	Treatment Area Thickness (feet)	System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
Hydrogen Release Compound (HRC) (Continued)													
Invensys Control	Old Saybrook, CT	Pilot and Full	Pilot - HRC, NA Full - HRC, 11,000 lb	NA	NA	NA	NA	NA	Pilot - NA Full - 55 injection points in an unknown configuration, unknown number of monitoring points.	Pilot - December 1999/9 months Full - September 2000/NA	Full scale application is currently in the process monitoring stage	NA	Electron donor injection was a viable remedial approach for chlorinated VOCs in this low permeability application. 80% of PCE mass was removed.
Manufacturing Facility	Brighton, NY	Pilot	HRC, 500 lb	$7.50	$3,750	None	560	NA	24 injection points installed in a grid with 5 foot spacing. 4 monitoring wells installed for process monitoring.	NA/NA	NA/NA	quarterly	Conditional Closure has been granted.
Rocky Flats Environmental Technology Site	Golden, CO	Pilot	HRC, 800 lb	NA	NA	NA	NA	NA	NA	April 2001 / 14 months	Full scale application is being evaluated	Monthly	HRC material was tremmied into soil boreholes
Arlington Cleaners	Arlington, TX	Full	HRC, 7,000 lb	$4.46	$31,200	None	3,000	15	45 direct injection points. 16 of the points were installed at a 15 to 30 degree angle to inject beneath a pre-existing structure. An unknown number of monitoring wells were installed for process monitoring.	May 2000 / Unknown	Process monitoring is ongoing	NA	During this application 1/3 of the injection wells were installed at a 15 to 30 degree angle to inject HRC under an existing building. Closure under the TNRCC VCP Program.
Cookville Manufacturing Facility	Cookville, TN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Applied in tight clay soils
Rice University Laboratory Study	Rice University, TX	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
River Terrace	Kanai, AK	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Massachusetts Military Reservation (MMR)	MA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Study conducted in 55-gallon soil reactors. HRC treament was very effective in removal of RDX, meeting treatment standards in 30 days.
West Union	West Union , SC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	More reducing conditions have been induced
Edible Oils													
Former Zipper Manufacturing Facility	Newport News, VA	Pilot	Vegetable Oil; 4,800 lbs	NA	NA	NA	200	10	Geoprobe injection at 33 locations	April 2000	Evaluate full-scale remediation	NA	NA
OU2, Defense Depot Hill Utah	Ogden, UT	Pilot	Vegetable Oil	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
OU4, Defense Depot Hill Utah	Ogden, UT	NA	Vegetable Oil	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hangar K, Cape Canaveral AFS	Cape Canaveral, FL	Pilot, Full	Vegetable Oil	$0.50 per lb	$5,700	None	Approximately 3,000	22 to 32 feet bgs	Thirty three injection points installed with CPT	Pilot - June 1999 to June 2000, Full-Scale - July 2000 to present	Evaluating performance and system expansion	Semi-annual	NA
Site N-6, Former NSA Mid-South	Millington, TN	Pilot	Vegetable Oil	$0.22 per lb	$10,104.00	None	Approximately 350	45 to 85 feet bgs	6,100 gallons of soybean oil injected into 8 injection wells staggered at depths of 45 to 85 feet bgs.	August 2000 to present	Evaluating performance and system expansion	Semi-annual	Additional injection or redistribution of substrate may be required
Site SS-015, Travis AFB	Travis AFB, CA	Pilot, Full	Vegetable oil	$0.34 per lb	$1,100	None	Approximately 2,800	12 to 22 feet bgs	Thirty eight injection wells installed with CPT. 28 wells failed and were replaced with 25 direct injection points.	Full-Scale - December 2000 to present	Evaluating performance and system expansion	Semi-annual	NA

Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description	Soil TOC (mg/kg)
Edible Oils (Continued)													
Site FF-87, Former Newark AFB	Newark, OH	Yes	PCE	Air Force	Ohio EPA	Accelerate groundwater restoration	Full	September 2001	Bruce Henry, Parsons 303-831-8100	Performance monitoring	Parsons, 2002a	Alluvial medium to coarse sand underlain by Pleistocene glacial silty clay	<34 to 2,400
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	Yes	PCE, TCE, VC	Navy	MPCA, EPA - Discharge to Surface Water	Field feasibility study	Pilot	November 2001	Dan Griffiths, Parsons 303-831-8100	Performance monitoring	Parsons, 2001	Glacial-fluvial medium to coarse grained sand	<500 to 7,100
Former Radiator Facility	IL	Yes	TCE	Industrial	NA	Field feasibility study	Pilot	September 2000	Paul Johnson, Parsons	Pilot test complete	Parsons, 2002b	Clayey sand	NA
Dover AFB, DE	Dover AFB, DE	No	TCE, DCE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Edwards AFB, CA	Edwards AFB, CA	No	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lumberton Dry Cleaning Facility	Lumberton, NC	No	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hamilton, NC	Hamilton, NC	No	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Long Island, NY	Long Island, NY	No	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site SS-17	Altus AFB, OK	Yes	TCE, DCE	Air Force	Oklahoma DEQ, EPA	Field feasibility study	Bench, Pilot	November 2001	Mike Lee, Terrra Systems, and Tony Lieberman, Solutions IES	Performance monitoring	Terra Systems, 2002	Reddish brown , moderately plastic, sandy clay to 15 feet below ground surface underlain by clayey shale with occasional gypsum layers.	NA
OU-1 Landfill 3	Altus AFB, OK	Yes	TCE, DCE	Air Force	Oklahoma DEQ, EPA	Field feasibility study	Pilot	November 2001	Mike Lee, Terrra Systems, and Tony Lieberman, Solutions IES	Performance monitoring	Terra Systems, 2002	Reddish brown , moderately plastic, sandy clay to 15 feet below ground surface underlain by clayey shale with occasional gypsum layers.	NA
Whiteman Air Force Base LF-08	Whiteman AFB, MO	Yes	TCE, DCE, VC	Air Force	Missouri Department of Natural Resources	Field feasibility study	Pilot	July. 2002	Dan Griffiths, Parsons 303-831-8100	Performance monitoring	Parsons, 2002f	Approximately 24 feet of dense clay overlying a clayey gravel zone which extends to the top of weathered claystone bedrock at 30 feet below ground surface.	240 to 710
Mulch and Compost													
Building 301, Offutt AFB	Omaha, NE	Yes	TCE	Air Force	Nebraska DEQ, EPA	Field feasibility study to accelerate groundwater restoration	Pilot, Full	Pilot: January, 1999 Full: July, 2001	Carole Aziz, Groundwater Services, Inc.	Performance monitoring	Haas *et al.,* 2000; Groundwater Services, Inc., 2001	Stiff to very stiff, reddish brown, low plasticity, silty clay	3.0 to 36
OU1 Landfill 3	Altus AFB, OK	Yes	TCE, DCE	Air Force	Oklahoma DEQ, EPA	Full-scale application to prevent surface water discharge and prevent potential off-base migration	Full	July 2002	Bruce Henry, Parsons (303) 831-8100	Performance monitoring	NA	Reddish brown silty clay	190 to 320
Naval Weapons Industrial Reserve Plant	McGregor, Texas	Yes	Perchlorate	Navy	TNRCC	Ground water restoration for offsite migration via a permeable reactive biobarrier	Bench, Pilot, Full	2000	Ronnie Britto, Ensafe, Inc.	Performance monitoring	Cowan, 2000	NA	NA

Site Name (Sorted by Substrate)	Site Location	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments	Total Orga Maximum Pre-Treatment (mg/L)
Edible Oils (Continued)													
Site FF-87, Former Newark AFB	Newark, OH	9 - 14	Unconfined aquifer with confining layer at 25 to 30 feet bgs	16 to 22 (upper) 0.016 to 0.24 (lower)	0.015	25 (est.)	403 (upper) 3.1 (lower)	Former hazardous waste storage area	PCE - 0.34 TCE - 0.013 DCE - 0.046 VC - ND Ethene - 0.00048	PCE - 0.74 TCE - 0.008 DCE - 0.036 VC - 0.020 Ethene - N/A	None	None	23
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	28 - 34	Shallow unconfined aquifer underlain by a discontinuous clay aquitard at 70 to 93 feet bgs	NA	0.008	25 (est.)	110 to 730	Manufacturing facility	TCE - 6.7 DCE - 0.22 VC - ND Ethene - ND	TCE - 6.2 DCE - 1.8 VC - 0.002 Ethene - 0.25	None	At approximately 5 months after injection TCE concentrations were approximately the same as baseline conditions. However, cis-1,2-DCE and ethene concentrations detected at 5 months post injection were substantially higher than the baseline event.	2.4
Former Radiator Facility	IL	5	Shallow unconfined aquifer	NA	NA	NA	NA	Manufacturing facility	TCE - 1.3 DCE - 7.4 VC - 0.22 Ethene - N/A	TCE - <1 DCE - 41 VC - 8.3 Ethene - N/A	NA	None	NA
Dover AFB, DE	Dover AFB, DE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Edwards AFB, CA	Edwards AFB, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lumberton Dry Cleaning Facility	Lumberton, NC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hamilton, NC	Hamilton, NC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Long Island, NY	Long Island, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site SS-17	Altus AFB, OK	8 - 10	Unconfined silty clay aquifer	NA	NA	NA	100	Industrial area	TCE - 1.66 DCE - 0.90 VC - 0.44 Ethene - 0.007	TCE - 0.65 DCE - 1.07 VC - 0.79 Ethene - 0.11	NA	Within approximately 5 months the TCE maximum concentration had been reduced by approximately 61%. DCE, VC, and ethene maximum concentrations increased by approximately 19%, 80%, and 1,470% respectively. TCE concentration reductions were observed in all of the injection wells and monitoring wells with per well reductions ranging from 13 to 99%.	7.7
OU-1 Landfill 3	Altus AFB, OK	8 - 10	Unconfined silty clay aquifer	NA	NA	NA	100	Landfill	TCE - 10.4 DCE - 0.5 VC - < 0.12 Ethene - < 0.03	TCE - 6.55 DCE - 0.8 VC - 0.24 Ethene - 0.79	NA	Within approximately 5 months the TCE maximum concentration had been reduced by approximately 37%. DCE, VC, and ethene maximum concentrations increased by approximately 60%, 80% and an order of magnitude, respectively. TCE concentration reductions were observed in all wells except injection well 6, with per well reductions ranging from 23 to 92%.	23
Whiteman Air Force Base LF-08	Whiteman AFB, MO	6	Unconfined clay aquifer. Groundwater flow is predominantly in the clayey gravel interval at 24-28 feet bgs.	0.06 to 0.2	0.016	25	1.4 to 4.9	Landfill leachate plume	TCE - 2.1 DCE - 0.033 VC - ND Ethene - <0.001	NA	None	The first process monitoring round is scheduled for October 2002.	< 5.0
Mulch and Compost													
Building 301, Offutt AFB	Omaha, NE	6	Shallow unconfined aquifer	3.5	0.01	15	84	Aircraft Manufacturing and Maintenance	TCE - 1.9 DCE - 0.27 VC - 0.0023 Ethene - ND	TCE - 1.22 DCE - 0.098 VC - 0.004 Ethene - 0.008	None	61 percent reduction in mean TCE concentration downgradient of biowall	24
OU1 Landfill 3	Altus AFB, OK	6 to 12	Shallow unconfined aquifer	8.4 to 43	0.003	10	0.25 to 1.25	Landfill Leachate	Upgradient Well TCE - 6.2 DCE - 0.85 VC - ND	Biowall Well MP-01 TCE - 0.048 DCE - 0.64 VC - ND	None	Concentration data after 4 weeks of installation. Limited evidence of degradation of TCE to DCE.	<10 (background)
Naval Weapons Industrial Reserve Plant	McGregor, Texas	NA	Shallow unconfined aquifer	NA	NA	NA	NA	Release of Ammonium Perchlorate as Rocket Fuel Component	Perchlorate - 27 (Pilot-Test)	Perchlorate - ND	TCE	Full-scale System Installed	NA

APPENDIX B - ENHANCED BIOREMEDIATION DATABASE

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	nic Carbon	Dissolved Oxygen		ORP		pH		Nitrate		Ferrous Iron		Sulfate		Methane		Scale of Application	Substrate Type, Amount, and Concentration
		Maximum Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mV)	Range Post-Treatment (mV)	Range Pre-Treatment (su)	Range Post-Treatment (su)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)	Range Pre-Treatment (mg/L)	Range Post-Treatment (mg/L)		
Edible Oils (Continued)																		
Site FF-87, Former Newark AFB	Newark, OH	500	0.20 to 1.78	NA	-74 to -238	NA	6.43 to 7.33	NA	0.04 to 0.08	0.01 to 0.05	0.09 to 3.49	Unknown	59 to 129	2 to 110	0.98 to 14	NA	Full	656 gallons of Vegetable oil emulsified with 2546 gallons of water
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	26,000	0.22 to 2.28	< 0.01 to 1.77	+74 to -158	-136 to -395	6.8 to 7.12	5.10 to 7.09	< 0.01	< 0.1 to 2.85	< 0.01 to 0.70	< 0.01 to 3.9	100 to 230	7 to 220	ND	ND	Pilot	3,600 gallons of Vegetable oil emulsified with 7,200 gallons of water
Former Radiator Facility	IL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot	330 gallons of straight vegetable oil
Dover AFB, DE	Dover AFB, DE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Edwards AFB, CA	Edwards AFB, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lumberton Dry Cleaning Facility	Lumberton, NC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hamilton, NC	Hamilton, NC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Long Island, NY	Long Island, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site SS-17	Altus AFB, OK	7,300	0.17 - 4.53	0.5 - 1.6	+70 - -173	-76 - -230	7.0 - 7.8	4.9 - 7.1	<0.5 - 0.3	< 0.5	0.01 - 1.16	NA	107 - 2,011	2.5 - 1,400	0.008 - 1.82	0.054 - 19.0	Pilot	Vegetable oil, 150 gallons as a 20% oil in water emulsion chased by 125 gallons of treated water.
OU-1 Landfill 3	Altus AFB, OK	11,000	0.16 - 3.8	< 0.1 - 0.6	+49 - +81	-51 - +138	7.0 - 7.2	4.7 - 7.0	2 - 6.1	<0.5	0.07 - 0.3	25 - 50	1,559 - 2,112	100 - 2,175	<16	16 - 890	Pilot	Vegetable oil, 50 gallons as a 20% oil in water emulsion chased by 110 gallons of treated water. 50 gallons of lactate and yeast extract.
Whiteman Air Force Base LF-08	Whiteman AFB, MO	NA	1.8 to 8.9	NA	-53 to +146	NA	6.96 to 7.92	NA	17 to 23	NA	< 0.007 to 0.34	NA	83 to 120	NA	0.001 to 0.002	NA	Pilot	Vegetable oil, 575 gallons emulsified with 1600 gallons water
Mulch and Compost																		
Building 301, Offutt AFB	Omaha, NE	Mean: 1.3	1.0 to 2.5	Mean: 0.03	133.2 to 182.6	Mean: 169.5	6.88 to 7.91	Mean: 6.44	<0.05 to 6.4	Mean: 16.75	<0.02 to 0.06	Mean: <0.2	35.0 to 74.6	Mean: 16.75	<0.0012 to 0.099	NA	Pilot and Full	Mulch
OU1 Landfill 3	Altus AFB, OK	2,800 (biowall)	<0.1 to 4.5 (background)	<0.1 (biowall)	20 to 107 (background)	-266 to -365 (biowall)	6.8 to 7.2 (background)	6.43 to 6.75 (biowall)	<0.1 to 9.5 (background)	<0.5 (biowall)	<0.1 (background)	3 to 4	1,600 to 2,200 (background)	410 (biowall)	<1 (background)	7.9 to 8.8 (biowall)	Full	Mulch
Naval Weapons Industrial Reserve Plant	McGregor, Texas	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Pilot and Full	Primarily compost, with some cottonseed and vegetable oil

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area: Surface Area (sq. ft)	Treatment Area: Thickness (feet)	System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
Edible Oils (Continued)													
Site FF-87, Former Newark AFB	Newark, OH	Full	656 gallons of Vegetable oil emulsified with 2546 gallons of water	$0.47 per lb	$2,372.00	None	Approximately 900	17 to 25 feet bgs	Three injection wells in sand unit and three injection wells in lower silt unit	Full scale - September 2001 to present	Evaluating performance	Quarterly	IT is performing performance monitoring sampling and reporting
Naval Industrial Reserve Ordnance Plant, Fridley	Fridley, MN	Pilot	3,600 gallons of Vegetable oil emulsified with 7,200 gallons of water	$0.39 per lb	$10,397	None	Approximately 400	40 to 50 feet bgs	Three injection wells in unconfined sand unit	Pilot - November 2001 to present	Evaluating performance and system expansion	Quarterly	One year results report will be submitted in May, 2003
Former Radiator Facility	IL	Pilot	330 gallons of straight vegetable oil	NA	NA	None	Approximately 80	5 to 15 feet bgs	Oil was injected into 1 shallow injection well	September, 2000	Evaluating performance	NA	Significant VC was produced within the treatment zone, corresponding with drastic decrease in TCE concentrations. Regulatory body is uncomfortable with going full scale due to VC production.
Dover AFB, DE	Dover AFB, DE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Edwards AFB, CA	Edwards AFB, CA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lumberton Dry Cleaning Facility	Lumberton, NC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hamilton, NC	Hamilton, NC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Long Island, NY	Long Island, NY	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Site SS-17	Altus AFB, OK	Pilot	Vegetable oil, 150 gallons as a 20% oil in water emulsion chased by 125 gallons of treated water.	NA	NA	NA	400	10	Six injection wells installed 5 feet apart in a barrier line configuration. Six new wells and 1 existing well were used for process monitoring.	December 2001	Process monitoring is ongoing	NA	6 injection wells installed in a barrier configuration with 5 foot well spacing.
OU-1 Landfill 3	Altus AFB, OK	Pilot	Vegetable oil, 50 gallons as a 20% oil in water emulsion chased by 110 gallons of treated water. 50 gallons of lactate and yeast extract.	NA	NA	Bromide, yeast extract, calcium chloride	400	NA	Two injection wells installed near an existing monitoring well.	NA	NA	NA	50 gallons of lactate and water from Site SS-17 (above) were injected into one of the two injection wells concurrent with the vegetable oil injection. Early results indicate bioaugmentation is not needed at this site.
Whiteman Air Force Base LF-08	Whiteman AFB, MO	Pilot	Vegetable oil, 575 gallons emulsified with 1600 gallons water	$0.53	$2,390	None	4,800	10	9 direction injection points and 10 monitoring wells installed.	July 2002 / 2 years	Process monitoring is ongoing	Semi-annually	Substrate was injected as an emulsion to increase the effective radius of influence and to improve the oil distribution in the subsurface.
Mulch and Compost													
Building 301, Offutt AFB	Omaha, NE	Pilot and Full	Mulch	$20.00 per yd^3 (estimated)	$10,960 (estimated)	None	Pilot: 100 linear feet Full: 400 linear feet	23 feet bgs	100-foot pilot biowall (23 feet deep) followed by a 400-foot (24 feet deep) full-scale biowall. Surface amendment pilot test.	Full - July 2001 to present (Full life span estimated to be approx. 10 yrs)	Evaluating performance	Bi-annual (approx.)	61 percent reduction in mean TCE concentration downgradient of biowall, 46 percent reduction in mean TCE concentration downgradient of surface amendment
OU1 Landfill 3	Altus AFB, OK	Full	Mulch	$10.00 per yd^3 handling cost (estimated)	NA	Cotton Gin Compost and Sand	455 foot linear barrier wall	4 to 24 feet bgs	455-foot long by 24-foot deep by 1.5-foot wide barrier wall	July 2002 to present, estimated life-cycle of 10 years	Performance monitoring	Bi-annual	Elevated TOC observed 5 to 10 feet downgradient of biowall within two months
Naval Weapons Industrial Reserve Plant	McGregor, Texas	Pilot and Full	Primarily compost, with some cottonseed and vegetable oil	NA	NA	NA	NA	NA	Permeable Reaction Barrier Wall	NA	Performance monitoring	NA	Used gravel in trench to maintain permeability

BIOREMEDIATION MANUAL

Summary of Information on Sites Implementing Enhanced In-Situ Bioremediation

Site Name (Sorted by Substrate)	Site Location	In Survey Tables	Contaminants of Concern	Responsible Party	Regulatory Agency	Remedial Objective	Scale of Application	Implementation Date	Point of Contact	Project Status/ Follow-up	References	Lithologic Description	Soil TOC (mg/kg)
Chitin													
Distler Brickyard Superfund Site	Louisville, KY	Yes	TCE, *cis*-1,2-DCE, VC	Industrial	EPA Region 4	Groundwater remediation to potable water standards	Pilot	October, 2001	Kent Sorenson, Northwind Environmental	Performance monitoring	Sorenson *et al.*, 2002	Relatively low permeability silts and clays	NA
Gaseous Hydrogen													
Launch Complex 15	Cape Canaveral, FL	Yes	PCE, TCE	Air Force	Florida DEP, EPA	Technology demonstration	Pilot	February 1999	Chuck Newell, Groundwater Services, Inc.	Completed pilot test	Newell *et al.*, 2000, 2001, and 2002	Silica sand with some shell fragments containing clay and organic matter to 70 feet bgs	NA
Offutt AFB	Omaha, NE	Yes	DCE	Air Force	Nebraska DEQ, EPA	Technology demonstration	Pilot	November 1998	Patrick Haas, Mitretek	Complete	Newell *et al.*, 2000	Sand	3.0 to 35.5
Twin Cities Army Ammunition Plant	New Brighton, MN	Yes	TCE	Army	Non-Regulatory	Technology demonstration for use of hollow fiber membranes to deliver hydrogen *in situ*	Bench, Pilot	August 2000 (first membrane installation)	Dr. Michael Semmens and Paige Novak, University of Minnesota	Pilot complete, Evaluating field transition plan	Novak *et al.*, 2002	NA	NA

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Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Depth to Groundwater (feet bgs)	Groundwater Occurrence	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity (percent)	Groundwater Velocity (ft/yr)	Site Use and Source of Contaminants	Maximum Pre-Treatment Concentrations (mg/L)	Maximum Post-Treatment Concentrations (mg/L)	Other Contaminants of Concern	Comments	Total Orga Maximum Pre-Treatment (mg/L)
Chitin													
Distler Brickyard Superfund Site	Louisville, KY	Approximately 35	Unconfined aquifer	0.03 to 0.31	NA	10 to 15 (est.)	NA	Brick production	TCE - 0.007 (est.) DCE - 0.09 (est.) VC - 0.016 (est.) Ethene - 0.027 (est.)	TCE - ND (est.) DCE - 0.058 (est.) VC - 0.009 (est.) Ethene - 0.011 (est.)	None	Intermittent wetting of contaminant zone by infiltration	NA
Gaseous Hydrogen													
Launch Complex 15	Cape Canaveral, FL	6 to 7	Shallow Unconfined	95	<0.0011	30	124	Former rocket launching facility	TCE - 87 DCE - 370 VC - 52 Ethene - 7.3	TCE - 66 DCE - 270 VC - 67 Ethene - 11	None	50 (at 15 feet from injection point) to 90 (at 3 to 6 feet from injection point) percent reduction in total chlorinated ethenes in treatment zone over 18 months.	NA
Offutt AFB	Omaha, NE	8 to 10	Shallow unconfined aquifer	3.5	0.01	15	84	NA	TCE - N/A DCE - 0.43 VC - N/A Ethene - N/A	TCE - N/A DCE - <0.005 VC - N/A Ethene - N/A	NA	Small scale pilot test, complete cis-1,2-DCE (over 99%) removal.	NA
Twin Cities Army Ammunition Plant	New Brighton, MN	NA	Shallow Unconfined	NA	NA	NA	NA	Former Army Munitions Plant	NA	NA	NA	A decline in concentrations of TCE and DCE was observed, with an increase in VC and ethene after a lag period	NA

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Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	nic Carbon Maximum Post-Treatment (mg/L)	Dissolved Oxygen Range Pre-Treatment (mg/L)	Dissolved Oxygen Range Post-Treatment (mg/L)	ORP Range Pre-Treatment (mV)	ORP Range Post-Treatment (mV)	pH Range Pre-Treatment (su)	pH Range Post-Treatment (su)	Nitrate Range Pre-Treatment (mg/L)	Nitrate Range Post-Treatment (mg/L)	Ferrous Iron Range Pre-Treatment (mg/L)	Ferrous Iron Range Post-Treatment (mg/L)	Sulfate Range Pre-Treatment (mg/L)	Sulfate Range Post-Treatment (mg/L)	Methane Range Pre-Treatment (mg/L)	Methane Range Post-Treatment (mg/L)	Scale of Application	Substrate Type, Amount, and Concentration
Chitin																		
Distler Brickyard Superfund Site	Louisville, KY	NA	NA	NA	NA	NA	NA	NA	0.3	0.35	2	3	30	1	0.2	425	Pilot	Chitin; 325 lb
Gaseous Hydrogen																		
Launch Complex 15	Cape Canaveral, FL	NA	8.0 median background	NA	NA	NA	NA	NA	5.8 median background	NA	NA	NA	NA	NA	0.027 - 3.7	0.033 - 3.1	Pilot	Gaseous Hydrogen mix with 48% hydrogen: 130 ft^3/day/well on day 1, 6 ft^3/day/well (days 1-120), and 60 ft^3/week/well (days 120+)
Offutt AFB	Omaha, NE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Single Well Pull-Push Pilot Test	Gaseous Hydrogen
Twin Cities Army Ammunition Plant	New Brighton, MN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Bench, Pilot	Membrane addition of hydrogen at concentrations of 62 to 855 nanomoles

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Summary of Information on Sites Implementing Enhanc

Site Name (Sorted by Substrate)	Site Location	Scale of Application	Substrate Type, Amount, and Concentration	Substrate Cost per Unit	Total Substrate Cost	Bioaugmentation or Amendments	Treatment Area: Surface Area (sq. ft)	Treatment Area: Thickness (feet)	System Configuration	Application Date/ Life Cycle	Site Status/ Site Follow-up	Monitoring Schedule	Comments
Chitin													
Distler Brickyard Superfund Site	Louisville, KY	Pilot	Chitin; 325 lb	$3.5-4 (estimate)	$1,140 to $1,300	None	Approximately 150	38	Slurry with sand during hydraulic fracturing of low perm medium - FRAC RITE^{TM} method at 3 locations	Intended to last several years	Performance monitoring	NA	None
Gaseous Hydrogen													
Launch Complex 15	Cape Canaveral, FL	Pilot	Gaseous Hydrogen mix with 48% hydrogen: 130 ft^3/day/well on day 1, 6 ft^3/day/well (days 1-120), and 60 ft^3/week/well (days 120+)	$0.05/scf	NA	None	Approx. 900	5 to 25 feet bgs	Low pulsed biosparging. Four sparge wells, 6 multi-level sample points, 20 other monitoring points.	18 months	Planning further testing at additional sites	Completed	Tracers show biological consumption of hydrogen. Methane competition did not hinder reductive dechlorination. Radius of influence 5 to 10 feet direct influence, 15+ feet indirect influence.
Offutt AFB	Omaha, NE	Single Well Pull-Push Pilot Test	Gaseous Hydrogen	NA	NA	None	NA	NA	1000 liters of groundwater was extracted, H2 and tracers were added, water was pumped back into the formation. After 48 hours a small volume of water was extracted and analyzed.	November, 1998. 42 hour life cycle	Pilot test complete	48 hour test	Dissolved recirculation pilot test at Offutt AFB planned for 2002
Twin Cities Army Ammunition Plant	New Brighton, MN	Bench, Pilot	Membrane addition of hydrogen at concentrations of 62 to 855 nanomoles	$0.11/scf	NA	None	Approx. 27	NA	Gas-permeable membranes in three rows of 15 wells spaced 18-inches on center	Pilot system run for approximately 20 months	Pilot complete, preparing field transition plan	Weekly to Monthly	Hollow fiber membranes were able to deliver hydrogen near predicted levels for extended period of time. Presence of VC and ethene suggest that hydrogen was able to stimulate dechlorination of TCE, either directly or indirectly via acetate.